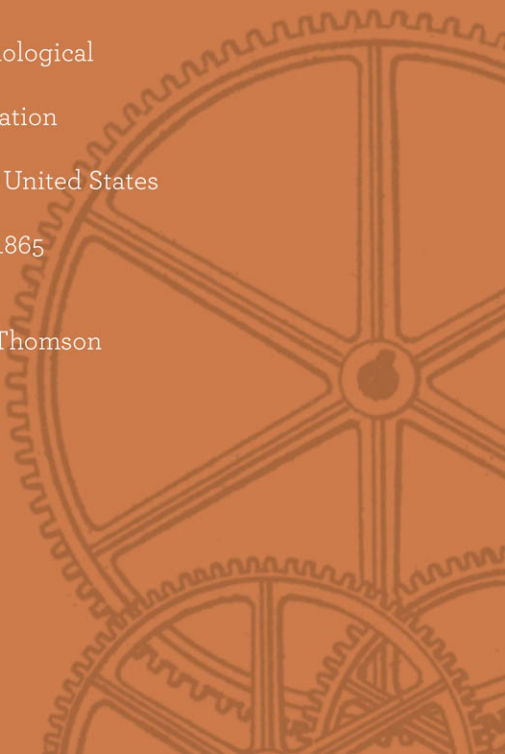
STRUCTURES OF CHANGE IN THE MECHANICAL AGE

Technological Innovation in the United States 1790–1865

Ross Thomson



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Structures of Change
in the Mechanical Age

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Structures of Change in the Mechanical Age

Technological Innovation in the United States, 1790–1865

ROSS THOMSON

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This book attempts to understand how the United States evolved from a relatively backward economy with little technological innovation in 1790 to a leading economy with widespread technological dynamism in 1865. The project has a long genesis. As a graduate student informed by such seminal thinkers as Adam Smith, Karl Marx, and Joseph Schumpeter and by the rich economic history literature, I concluded that technological innovation was at the core of long-run economic development and that innovation and the institutions shaping it evolved together. Economic history was too narrow to understand such innovation; business and technological history were indispensable. I initially explored the nineteenth-century evolution of U.S. sewing and shoe technologies, which led me to conclude that innovation followed paths that created and spread techniques along with organizations, markets, occupations, and other institutions to develop and use those techniques. Paths in many industries supported each other, making possible a trajectory that propelled development in whole economies. This insight led to the effort in this book to understand how paths of institutionally structured learning within and across industries shaped the technologically dynamic economy of 1865.

Knowledge of how economies developed, like the technological knowledge that informed that development, is a social product, and my research has benefited from interactions with many scholars. William Parker and Robert Heilbroner were particularly important in shaping my first book and my approach to research. These great economists, who both died in the past decade, combined a focus on significant issues, a critical eye to orthodoxies, superb scholarship, powerful yet graceful writing accessible to the public, enormous support for other researchers, and a deep commitment to human welfare. I dedicate this book to their memory.

Many scholars have perceptively commented on parts of the manuscript or

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My work could not have been conducted without those critical institutions that allow research to proceed and see the light of day: libraries, universities, and presses. Dozens of librarians directed me to sources, including those at the National Archives in Washington, D.C., and College Park, Maryland, and at state archives in Connecticut, Delaware, Maryland, New Hampshire, New Jersey, and New York. University librarians at Brown, Columbia, Harvard, Harvard Business School, New York University, Stanford, UCLA, and University of Vermont offered enormous assistance. Without the contributions of librarians at the New York Public Library, the American Precision Museum, the Rhode Island Historical Society, and especially the Hagley Museum and Library, essential evidence would have remained unearthed. Sabbaticals at the University of Vermont and visiting scholar appointments at Stanford and UCLA provided time and place for research. I thank Bob Brugger at the Johns Hopkins University Press for his editorial direction and Elizabeth Gratch for her many clarifications of the manuscript. Finally, for the past fifteen years, Floria Thomson has supported every aspect of the project, joining me in ten libraries, commenting on each stage of the manuscript, and telling me when enough was enough.

Structures of Change
in the Mechanical Age

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CHAPTER ONE

Structure and Change

In the Paris Universal Exposition of 1867 U.S. technology came in for high praise. Americans received grand prizes and gold medals for reaping and mowing machines, sewing machines, firearms, machine tools, steam engines, telegraphs, locomotives, and woodworking machines. Locks, scales, looms, machine-sewed shoes, and petroleum garnered silver medals. Such awards were unanticipated in London's Crystal Palace Exhibition sixteen years earlier, when reapers and revolvers surprised the public. By the time of the Paris Exposition Europeans expected Americans to invent widely and effectively. They were right; over the next half-century annual patenting almost quadrupled, after having expanded 13-fold since the Crystal Palace Exhibition, mechanization penetrated virtually every industry, electrification transformed workplaces and homes, labor productivity more than doubled, and the United States became the world's economic leader.[1]

The rapidly mechanizing United States of 1865 contrasted starkly with the preindustrial country at independence, when productivity grew slowly, if at all; machines were few and rudimentary; a machinery industry did not exist; and large industrial firms were rare. The contrast points to the classic problem of how industrialization began and became ongoing. How could the United States succeed in innovating so widely and deeply? Alfred North Whitehead famously remarked, "The greatest invention of the nineteenth century was the invention of the method of invention."[2] That method generated sustained technological change through the operation of key institutions. The antebellum United States developed such a method, but it was not the organized, science-based research Whitehead had in mind. In the earlier method quite different institutions structured learning in ways that developed new techniques and new capabilities to deepen and widen invention. Understanding the institutions will prove essential for an account of antebellum industrialization. Reflecting on a postbellum innovation will help identify their character and operation.

An Outcome: The Wizard of Menlo Park

Perhaps the most famous American innovation was Thomas Edison's incandescent light. It succeeded as part of an electrical light and power system that included generating plants and distribution facilities. Success required sufficiently large markets, competitive advantages over gas lighting, and large investments. Edison's brilliance, leading the press to dub him the "Wizard of Menlo Park," surely mattered. But more was required. Edison's prowess rested on his knowledge and his access to the knowledge of others. Edison had learned how to learn and how to form a team of coworkers who did the same.

The team originated in Edison's earlier inventions. Trained as a telegraph operator, Edison adapted telegraph technology in his first inventions, an electric vote recorder and a stock and gold ticker. With revenue from ticker sales, in 1870 he built a Newark plant to manufacture tickers and to develop technology. Here he formed his first inventive team, including a group of machinists, designers, model makers, and experimenters who remained with Edison in Menlo Park. Its remarkable successes, expressed in Edison's 98 electrical patents through 1876, included telegraphs that sped communication and that transmitted four messages simultaneously. Sale of the team's products—both equipment and patents—financed Menlo Park in 1876.[3]

Menlo Park was an "invention factory" and was designed accordingly. It consisted of a lab with electrical devices and chemicals, a machine shop to build prototypes and electrical machinery, buildings for lamps and other inputs, and an office with a drafting room and a library of patent materials and scientific and technical publications in several languages. Edison's team broadened invention from telegraphs to electrical inventions and beyond, including basic carbon transmitter telephone patents and the phonograph. When, after talking to scientists, Edison shifted attention to the electric light, he found he had to hire scientists and specialized craftsmen. Employment grew from 15 in August 1878 to 25 in mid-1879 and 35 by year's end. He experimented simultaneously with electric lighting and with power generation and distribution. The experiments led to a series of critical conclusions, such as the necessity of a vacuum (and a bulb to preserve it) and high electrical resistance in lamps. Although not frontier science, the experiments were purposive, informed by the technical literature, and solved a sequence of key problems. In about a year Edison developed his basic lighting invention and key elements of the power generation and distribution system, manifested in 16 patents in 1879 and 1880.

Edison developed and commercialized his invention in companies in which he

shared ownership rights. The Menlo Park team made prototypes of more durable bulbs, routinized vacuum pumping, simplified connections with the screw-in socket, and improved the dynamo. Team members led Edison companies to manufacture lamps and other equipment. On September 4, 1882, Edison turned on the system from J. P. Morgan's office. Although much invention would be required to build an electrical system, including nearly 400 more Edison patents by 1890, the practical incandescent light had come into being, along with new knowledge and means to spread it.

Edison's success rested on the prior development of knowledge-generating and transmitting structures, each of which had originated by 1865 without any reference to electric lighting. The most directly relevant centered around the telegraph, including telegraph companies, telegraphers, electrical engineers, and instrument makers. Telegraphy supplied critical knowledge, agents, inputs, and finance. One legacy was Edison himself, whose learning as a telegraph operator, inventor, and instrument maker shaped later inventions. Others on his team had similar backgrounds. Outside electrical innovators included Moses Farmer, a leading telegraph inventor who wrote Edison about carbon as a filament. Telegraph and telegraph instrument firms supplied financing and inputs.[4]

Machinists formed a second critical structure. They produced the delicate, complex electrical equipment Edison used to develop his inventions, translated his ideas into experimental models and testing equipment, and invented mechanical features of the system. Telegraph instruments were light and battery run, and Edison relied on machinists to make and perfect much heavier electricity-generating equipment. He also relied on machinery firms for dynamos, vacuum machines, machine tools, and, not least, trained machinists.[5]

Finally, Edison benefited from occupations and voluntary groups that facilitated invention. Patent agents, draftsmen, and model makers knew mechanical principles and how to represent them with words, drawings, and models, which helped perfect and patent inventions. Patenting conferred property rights, which Edison sold to finance lighting research and then parlayed into stock ownership in lighting and power companies. Edison's patent agents included Carroll Wright, who had been U.S. commissioner of patents, and Lemuel Serrell, who had prepared patent claims since 1838. As Edison's patent searches demonstrated, patenting also communicated knowledge.

Engineers and applied scientists were linked to telegraphy and inventive institutions. Like Edison's early partnership, advertised as a "Bureau of Electrical and Telegraphic Engineering," independent electrical and mechanical engineers sold research services, developed inventions, and manufactured new products.[6] Edison

was in close touch with the engineers of his day, such as Boston's Charles Williams, the telegraph instrument maker in whose shop Edison made his first invention and where Alexander Graham Bell and others congregated and invented. Scientists, often associated with colleges, consulted with inventors and communicated scientific knowledge. Two Bowdoin graduates who studied mathematics and science in Germany became principal collaborators in developing the light and power plants. The broader inventive community included publishers of technical books and journals, including the *Telegrapher* and *Scientific American,* which both featured Edison's inventions, and civil organizations that sponsored industrial exhibitions, lectures, and experiments.[7]

Edison's experience illustrates the thesis of this book: technological change was a process of institutionally structured learning in which innovators gained knowledge through established communication channels, and innovations spread knowledge in ways that fostered further innovation. Learning derived in part from knowledge generated for other applications, and this technological convergence, as Nathan Rosenberg calls it, solved inventive problems.[8] Knowledge was socially organized. Firms, markets, and occupations transmitted it, as did patenting systems, publications, schools, and civil organizations. In capitalist economies knowledge is distributed unevenly, and inventors more readily succeed when they hold relevant knowledge or have access to it. Networks of interacting individuals provided the access. Market interactions supplied knowledge embedded in machinery, workers' capabilities, and technical publications. Innovators also acquired knowledge through noncontractual interactions of inventors and skilled practitioners. Networks involved mobility of workers among firms and the formation of new firms. Networks had a geographic dimension, and so did knowledge and invention. Innovators organized knowledge, workers, and equipment to complete and diffuse inventions and in the process formed new networks. Successful innovations spread knowledge, leading to continued innovation and such unintended outcomes as Edison's light.[9]

The electric light illustrates one critical outcome of economic development through the Civil War: even in new industries inventors could rely on established institutions to meet conditions for their success. Machinists, telegraph experts, and invention-supporting professions were parts of technological centers—that is, occupations, industries, services, or organizations whose practitioners held and developed widely applicable technological knowledge and transmitted it among industries. Three centers—machinery, engineering and applied science, and inventive institutions—supplied conditions for many innovations, including each of the innovations for which Americans won awards at the Paris Exposition. Centers

enabled new industries to build on older ones and fostered innovation in established industries. Technological centers and industry networks formed structures of change, and by the Civil War they made technological innovation ongoing.

Moving Backward: Four Providence Mechanics

To understand ongoing industrialization requires accounting for the origin and operation of institutions that structured learning. The institutions that supported innovations in 1865 had little reality in 1790. How did they come into being? How did they operate? How did technology change before they existed? Four mechanic-inventors from one town nicely illustrate the issues, especially when examined backward, from the end to the beginning of the period.

Joseph R. Brown was a leading machinist and machine tool producer during the Civil War. From the 1850s Brown's precision instruments enabled accurate measurement on the shop floor. Late in the decade he contracted to mass-produce sewing machines. Brown readily purchased machine tools and acquired knowledge of mass production metalworking from the firearms industry. Partly to make sewing machines, he invented a series of machine tools, including the premier toolroom machine, the universal miller. Patented in 1865, it spread widely and quickly; firms making 20 different kinds of products used it by 1867. Brown clearly deserved the medals his machine tools won in the Paris Exposition.[10]

George Corliss was the most famous Providence machinist at the end of the Civil War. His notoriety arose from his innovative steam engine. His saga began in 1844, when he moved to Providence to commercialize a patented sewing machine but accepted a position as a draftsman in an engine-making firm instead. His engine, patented in 1849, marked the most important advance since the high-pressure engine early in the century. Its complexity placed a premium on accurate construction. Markets for machine tools were less well established than when Brown sold his equipment, but Providence was already a center of machinery production, and Corliss's employer had purchased one of the country's first metal-planers in 1838. Corliss used local capabilities, patented a gear cutter and other metalworking equipment, and later purchased Brown and Sharpe's milling machines and turret lathes. Corliss benefited from attorneys and experts who successfully enforced his patents. By the Civil War he had taken out 15 patents, and he received many more after the war. Like Brown, Corliss secured sales in many industries.[11]

Twenty years before Corliss's success, another Providence engine inventor had failed. Zachariah Allen was a textile manufacturer and inventor. In 1834 he patented

a cutoff mechanism to increase the control and fuel efficiency of steam engines, but the firm that produced it did not survive. One reason for the failure is revealing. When Corliss won the Rumford Medal from the American Academy of Arts and Sciences in 1870, Allen protested on two grounds. First, he and others had earlier invented similar cutoff mechanisms, which were known in Providence when Corliss entered engine making. This argument might have been sour grapes, but Allen added a second ground, that Corliss benefited from production capabilities far better than those Allen could obtain. In this respect he was right; although Providence was already a center of machine tool usage, no one in the United States used the metal-planer in the early 1830s, and the engine lathe had only modest usage. Both were needed for accurate production. Corliss also benefited from the emerging demand for steam power among textile manufacturers. Nor could Allen command the services of patent agents, who largely originated after the patent system's fundamental restructuring occasioned by the Patent Act of 1836.[12]

A quarter-century before Allen's engine, David Wilkinson ran one of the country's initial textile machinery firms. His most prominent customer was Samuel Slater, the industry leader in cotton textiles. Textile machinery demand was too small for specialization, and Wilkinson found other markets. Utilizing his blacksmith training, he invented a metalworking lathe to make large screws, which he patented in 1798. As developed, it applied to machine making throughout the economy and to such universally used products as screws and bolts. Yet Wilkinson sold no lathes and secured only a few orders for casting lathe parts. The lathe spread less through his own activity than through the mobility of his workers, who used it to make textile machines, screws, and machine tools. Patent licensing was even less important; after Wilkinson personally scoured the East Coast to find if others used his principle, his patent found only one licensee. Diffusion was halting; Philadelphia acquired the industrial lathe by discovering the British Maudslay lathe, even though one of Slater's workers made textile machinery in that city. Finding markets too thin, Wilkinson went into textiles and iron founding and secured no more patents in metalworking, though workers he trained received many.[13]

Looking backward, one observes a peeling away of the conditions that benefited Edison's invention. This was particularly clear for machine-making capabilities. Brown had to redesign purchased lathes and invent his own machine tools to make sewing machines. Corliss benefited from his emigration to a leading metalworking center, but even in Providence success required extensive investments in improving his metalworking capabilities. Allen was not so lucky because the Providence of his day had fewer engine makers and much less mechanical capability. Wilkinson enjoyed none of the benefits of an established machinery sector, nor did he find

markets for his lathe. Earlier inventors faced added barriers in the weak development of occupations connected to patenting, drafting, model making, and engineering. Pure science barely affected the Providence inventions, but publications about the "science of mechanics"—the organized description of mechanisms and machines—benefited later inventors far more than earlier ones. Later inventors could draw on knowledge and machinery developed for other purposes; technological centers came to play a progressively more important part in ongoing technological change over the course of the antebellum period. The same was true for nonmechanical technologies. The first telegraph firms found themselves in a position similar to Wilkinson, with the basic difference being that they relied on scientific institutions and a machinery sector.

The examples also reveal that throughout the period interactions within industries and their equipment suppliers structured technological change. Wilkinson and other textile machinists, some of whom he had trained, diffused and improved the textile machines so essential to industrialization, setting the stage for Allen's textile inventions. They formed innovational networks involving new occupations that spread new techniques and knowledge. Corliss may not have known about Allen's engine cutoff patent, but he surely learned from the Providence engine-making network. Likewise, Brown learned from the stream of Providence metalworking firms. The geographic dimension of such interactions conferred advantages on innovators located where technology-transmitting networks operated. Innovation took on a cumulative quality within and between industries, which supported later invention and allowed it to address technological problems that could not have been solved earlier.

Understanding the Innovation System

Edison and the Providence mechanics illustrate the core themes of the book. Partly as a result of innovations, a dense system of institutions arose in the antebellum United States that communicated and expanded technological knowledge, a system linking firms, markets, occupations, the Patent Office, civil organizations, educational establishments, scientific societies, and governmental agencies. They generated and diffused techniques and also developed capabilities to continue inventing. As such, they structured change, and through them invention came to be ongoing.

Scholars of twentieth-century technological change have called the interlinked set of institutions that generate and spread new techniques an "innovation system." The system is not planned by organizations with the goal of spawning technological change at a societal level. Rather, it is made up of firms, individuals, and

organizations that interact to generate inventions and technological capabilities. Innovation systems have a national dimension; governments, civil organizations, and firms spread knowledge more fully within than between nations.[14] Such institutions help account for the pace of technological change and its differences among nations.

Analysts of innovations systems focus on economies in which large, managerial firms, organized private research and development, and massive, government-funded, often university-based educational and scientific activity combined to generate streams of scientific discoveries and new techniques. None of these factors played a large role before 1865. Firms were small and mostly proprietary, inventors commonly doubled as producers, and technological knowledge was acquired on the job and through publications and civil organizations. Yet key outcomes were similar to those of twentieth-century systems: technological knowledge developed, spread, and gained usage. Feedbacks supported new innovation. Use generated more knowledge and strengthened transmitting institutions; new knowledge deepened use and fostered institutional growth, and institutions spread knowledge and techniques. An innovation system emerged by the Civil War but one quite different from the modern system. Because technological change was episodic before about 1790, the mid-nineteenth-century system can be thought of as the first innovation system in the United States. If innovation systems structured economic development in industries and whole economies, then a study of the first U.S. innovation system is indispensable to understanding the American Industrial Revolution.

This book examines the structure, formation, and significance of the antebellum U.S. innovation system. Any innovation system communicates and organizes knowledge in ways that direct innovation. Several features of knowledge are relevant in this regard. First, knowledge is (and was) a public good, in the sense that many individuals can simultaneously hold it, and it is difficult to exclude others from it. Thomas Jefferson grasped this concept when he characterized an inventive idea: "Its peculiar character . . . is that no one possesses the less, because every other possesses the whole of it. He who receives an idea from me, receives instruction himself without lessening mine."[15] Public goods typically are underproduced by private actors, often requiring the government to play an active role. Second, knowledge is incomplete. Even in established industries, knowledge of future demand and competitors' behavior is at most partial. Innovation is far less certain; innovators simply cannot know the difficulty of developing a new technique, the need it will meet, and the innovative efforts of other firms. Because of the uncertainty, technological change is exploratory and evolutionary. Third, knowledge

is unevenly distributed. Institutions divide knowledge, resulting in information that is asymmetric and organized into networks of people who hold and transmit particular types of knowledge. Individuals in the networks get knowledge more cheaply, quickly, and completely than others. It makes a great deal of difference whether networks limit knowledge to a few people or spread it widely.

Finally, some knowledge has a universal quality that applies to many industries, while other knowledge is specific to an industry or operation. Knowledge can be universal if the same technique applies widely, such as a steam engine, or if different techniques share technological principles. In the same year as the Paris Exposition, Karl Marx argued that modern industry gave rise to the "modern science of technology," which dissolved the "varied, apparently unconnected and petrified forms of the social production process . . . into conscious and planned applications of natural science." This science was a powerful stimulus to technological change that could bind whole economies together. Innovation in turn expanded knowledge, and these feedbacks have been critical to ongoing technological change.[16]

Institutions structured innovation because they governed the extent, limits, and unevenness of the spread of knowledge and the incentives to develop new knowledge. Because the institutions of the antebellum innovation system differed greatly from the research and development system of the late twentieth century, the method of invention must have differed as well. In the research and development (R&D) method, of which Edison was one originator, professional researchers, often trained in universities and colleges, used scientific knowledge to develop new techniques. R&D was anticipated before Edison, but technological change overwhelmingly had other sources. The antebellum innovation system operated within industries and their capital goods suppliers, in which learning in networks structured internal dynamics. From this point of view the economy was a combination of distinct processes. The system also spanned industries. Much applied knowledge developed in one industry also solved problems in others. Such cross-industry knowledge underpinned ongoing change and shaped a distinctly American technology. This technology is often associated with the "American system" of interchangeable-parts manufacturing, which was important in a few sectors. But a far broader development of mechanization, civil engineering, and electrification linked many more industries.[17]

Understanding an innovation system is a vast project. This book focuses on the development and spread of technological knowledge, paying less attention to demand, the supply of finance, and learning how to use the new technique, though all were important for technological change and productivity growth.

So narrowed, an account of the antebellum innovation system must solve three problems. First, how did industrialization begin in the absence of developed technological centers? Early techniques could have diffused from England or the Continent, emanated from extraeconomic scientific or political developments, or developed within the U.S. economy, perhaps led by millwrights, smiths, and other crafts with mechanical or metalworking knowledge. Whatever the source, novel techniques involved new firms and occupations, which gave rise to unintended consequences that propelled innovation; Wilkinson, for example, hardly planned for his workers to set up their own textile machinery firms or spread his metalworking innovations. Early technologies developed in different paths, each limited by the absence of institutions that spread knowledge across industries.

The second problem is to demonstrate how technological centers formed and evolved. How could institutions within industries become or generate institutions of wider impact? That is, how did an "uncentered" economy become one in which institutions transferred technological knowledge between industries? Providence mechanics provided insights. Wilkinson cast machines to make firearms as well as textiles, and his workers spread their skills into hardware and machine tools. Brown and Sharpe had a similar effect on postbellum machinists, who moved into sectors as distant as automobiles. Extraeconomic organizations such as mechanics' associations, colleges, and scientific societies also spread knowledge across industries. Each institution provided means to utilize the universal quality of technological knowledge. By the 1830s technological centers were developed enough to support technological change in existing industries and in new ones. Identifying the relevant institutions is a central task of this book.

The third problem is to understand how technological centers modified paths of ongoing technological change within industries and originated paths in others. As Corliss and Brown illustrate, some commodities were used in many industries. Skilled workers could invent widely and set up firms in various industries. Centers could have been essential to develop radical new technologies, such as the locomotive, sewing machine, and reaper. Moreover, some centers may have complemented others, as advances in mechanics, applied science, and patent systems together supported development in many industries.

Explaining the development of the early U.S. innovation system requires establishing patterns across much of the economy without losing sight of individual innovators. A combination of diverse sources proved indispensable in the task. Targeted studies of many industries were needed to understand the variety of innovation paths, and I examined 14 industries in detail, including the 6 biggest manufacturing industries in 1860 and important parts of the transportation,

communication, and agriculture sectors. Such studies must focus on both leading innovators and more typical inventors; patents, firm records, publications, and biographies help provide the balance. I examined many institutions of cross-industry significance, including occupations (machinists, engineers, patent agents, and patent examiners), the patent system, colleges, the technical press, mechanics' institutes, and selected governmental agencies. One could not undertake this investigation without the aid of a strong secondary literature; economic, technological, and business histories were essential. Several kinds of primary sources were also critical (see appendix). Fifty data sets surveyed 14,000 patents issued to 5,500 inventors, over one-fifth of all patents through 1865. Some 6,000 patent assignments provided insights into the use of inventions and the role of the patent system in it. Industrial exhibition records cast light on the spread of knowledge and inventions and offer a counterbalance to the reliance on patent data. Primary records of two dozen firms helped identify the structure and functioning of antebellum firms, with an eye to assessing how knowledge was used, developed, and transmitted. Census data, both published and in manuscripts, provided a firmer understanding of economic organization. Contemporary journals and books detailed the character and transmission of technological knowledge.

An account of an innovation system must explicate its distinct parts without losing sight of their interactions. My strategy is to examine innovation in specific sectors and across the economy, then to consider institutions that integrated the innovation system, and finally to investigate the operation of the system and its importance for technological change through the Civil War. In particular, chapters 2 through 4 address the paths of technological change in six industries that began to mechanize by 1835, the further development of these industries through the Civil War, and the breadth of innovation. The study reveals the operation of institutions common to many sectors and the differences of innovative paths. Chapters 5 through 7 examine three technological centers: the machinery sector, the applied science nexus, and the patent system. These institutions help illuminate and connect industry dynamics. The next four chapters investigate major economy-wide outcomes of the innovation system, including the birth of major new techniques, linkages among sectors, and the cumulative effects on innovation in the last decade of the period.

As a whole, the book presents an interpretation of U.S. technological innovation from 1790 through 1865. Dynamics occurring within particular industries, complemented by the development of knowledge and institutions outside the economy, gave rise to machinists, engineers, patent agents, patent examiners, and others with widely applicable knowledge who in turn formed the core of the U.S.

innovation system. They were essential to the process of cumulative technological change. The process began in a number of industries with substantial craft skills, augmented by the relatively independent development of civil engineering, educational institutions, mechanics' associations, and the patent system. Innovations generated new techniques, new occupations, and new knowledge-spreading networks that enabled invention to continue. Over time the once-distinct dynamics became more interlinked. In the decade from the late 1820s to the late 1830s—just as Thomas Carlyle characterized the epoch as the "Mechanical Age"—interlinkages had real success in spreading machinery within and among sectors, overcoming limits to production, bringing science to industry, and deepening the training of technological occupations.[18] Partly as a result of the integration, innovation processes after 1835 were wider, more mutually informing, and capable of supporting major new technologies. Hence, innovation can be periodized around the mid-1830s, when technological centers surrounding machinery, applied science, and invention came to modify innovation within industries and in new ones. The widespread innovation over the next three decades was grounded in such institutions and extended and reshaped them, helping to explain how a former colony could so transform itself that the marvels it presented to the Paris Exhibition were no longer unexpected.

Paths of Initial Mechanization, 1790–1835

In the half-century after the United States gained independence, mechanical technologies transformed important industries and services. Textile machines, steam engines, and steamboats held the attention of contemporaries. Less-heralded changes reshaped printing, woodworking, clock making, and firearms. Such innovations helped bring industrial capitalism to an economy of small, unmechanized producers. In the process new institutions, including industrial firms, technological occupations, and governmental organizations, used and spread knowledge. Through such institutions technological change became ongoing.

The classic question of how mechanization could begin and continue in the late eighteenth and early nineteenth centuries took a particular form in the United States. Compared to Britain and much of Western Europe, the American economy was particularly agrarian, with limited mechanical skills and few institutions to spread technological knowledge, and yet its mechanization was especially broad. Mechanization followed different, largely independent paths for different technologies. Each path pioneered and diffused the new technique, made machines, and evolved though new institutions. And at the beginning each faced fundamental barriers.[1]

Prospects and Barriers

At independence Americans had good reason to expect output growth but not technological change. Benjamin Franklin formulated a law that U.S. population doubled every 20 years, which was remarkably accurate. He rightly thought that population could grow without impairing living standards; per capita income had not fallen, and probably rose a bit, over the eighteenth century. As Thomas Jefferson recognized, Malthusian population pressures did not impair well-being if new land

could be settled. The United States remained overwhelmingly agricultural, with three-quarters or more of the labor force in this sector as late as 1800. It was also commercial, and markets grew as output expanded.[2]

While output rose consistently, productivity did not. Agricultural productivity grew in places, such as around Philadelphia, where labor productivity increased by perhaps 20 percent over the eighteenth century, due in part to greater investment per worker. But family farms distant from large markets experienced little productivity change. With some exceptions, such as the American ax, techniques came from Europe and, for corn and other products, from Native Americans. Some nonagricultural sectors grew more rapidly. Productivity in ocean shipping, the second biggest sector of employment, grew close to 1 percent per year, due less to new techniques than to organizational improvements, such as more annual trips per ship. Artisans increased productivity little, though they occasionally reorganized production for regional markets. Growth occurred largely by extending small-scale production with unchanged techniques.[3]

Americans could well expect more of the same. Early leaders from Jefferson to Alexander Hamilton looked to mechanization for productivity growth. Widespread mechanization required a ready supply of labor, ample capital, large markets, and considerable knowledge and skill. Each of these factors posed a barrier. Hamilton knew—probably more than any other leader in the early Republic—that large-scale manufacturing could succeed only if it overcame the scarcity and high cost of labor. He noted several elements of a solution, each followed in the nineteenth century: manufacture in areas with high population densities, employ women and children, use machinery extensively, and encourage immigration. At independence these solutions were far off. Hamilton recognized that the inadequate investment blocked mechanization, especially in the large-scale establishments he advocated. At independence the United States had much less wealth than England, perhaps one-third as much per person if slaves are excluded. The financial limit could be overcome by bank credit, imported capital, or public funds. As secretary of the Treasury, Hamilton helped by establishing the first Bank of the United States, funding the government debt, and stabilizing the banking system. To secure investment in new fields, especially when faced with European competition, Hamilton advocated such governmental inducements as subsidies, tariffs, export and import controls, prizes, and property rights for inventors and importers of new techniques. Markets were much smaller and less integrated than in Britain, though colonial growth had reduced this barrier. Regional markets were integrating, as indicated by price convergence for agricultural and other commodities. Yet urbanization remained low, and interior transportation was costly.[4]

The United States could not match European knowledge of crafts, machinery, or applied science. Public policies supported knowledge diffusion but could not overcome technological backwardness on their own. Common school education was widespread in many northern colonies, and especially in New England illiteracy was rare among native white adults. Literacy rates were higher than in England and would remain so through the Civil War. Higher education would grow, including Jefferson's University of Virginia. Education created at least a minimal capacity to absorb written knowledge. Rejecting fiscal for communication rationales, the Post Office Act of 1792 laid the basis for a huge expansion of mail deliveries. Letters per capita grew fivefold from 1790 to 1800, and newspapers per capita doubled. Post offices grew even faster, expanding 12-fold from 1790 through 1800. Critical to extending trade by transmitting business correspondence and bills of exchange, the system also transmitted technological knowledge.[5]

Most directly linked to innovation, the Patent Act of 1790 created property rights for useful, original improvements in techniques. It built on the British system and offshoots in the American colonies but simplified and reduced the costs of the former and nationalized the effects of the latter. It aimed to provide incentives for individuals to invent, with the expectation that the invention and knowledge of it would benefit society. Under the law, as revised in 1793 and 1836, patenting increased enormously. George Washington and Hamilton favored extending protection to those who introduced techniques from abroad, but legislation rejected such a provision.[6]

It was in this setting of small markets, scarce capital and labor, and limited technological knowledge that the American Industrial Revolution began. Technological change was initiated from abroad; from "above," led by political and scientific institutions; and from "below," through the actions of self-interested innovators. Hamilton looked primarily abroad for knowledge of large-scale industry. Most innovators failed. The "Report on Manufactures" described a new woolen establishment as a "precious embryo," promising but precarious. Its manager identified the challenge: "We were . . . not only totally unacquainted with the various parts or subdivisions of the Labour; but equally destitute of every kind of Machinery and Labourers for executing such a project." Like others, they sought knowledge from British workers "bred to different branches of the Woolen and Worsted Business," often army deserters or prisoners. Troubled by "every kind of embarrassment which can attend the setting up of a new Business; either from the Ignorance, the Knavery or the fickleness of the workmen; the high price of materials; the smallness of our Capital, and the prejudices of the Community against *home made* Cloths," this precious embryo did not flourish.[7] As firms painfully learned, techniques could not transfer unless

users supplied labor, capital, and design and production capabilities. The United States would develop this absorptive capacity slowly and unevenly.

For Hamilton the cotton mill was the highest exemplar of mechanization, and water frame spinning machinery was its core. For the "immense progress, which has been so suddenly made in Great Britain" was the "prodigious effect" of such machinery. The "Report on Manufactures" singled out a Providence establishment, Almy and Brown, for having "the merit of being the first in introducing into the United States the celebrated cotton mill." At first Moses Brown failed in trying to develop Arkwright machinery based on "models belonging to the State of Massachusets which was Made at their Expence by Two persons from Scotland who took their Ideas from Observation and not from Experience in the Business [*sic*]."[8] Observation was not enough; Brown found experience in Samuel Slater, who had constructed and superintended Arkwright mills in England. Slater designed a system of machines modeled closely on Arkwright principles, built a modest mill, recruited and organized workers, and earned respectable profits in the face of English competition. This mill was the principal point of origin of the American cotton textile industry.

The government or voluntary associations might also develop techniques. Such innovation from above came from organizations seeking not profits but, rather, to provide conditions to initiate and sustain technological change. Patents, bounties, tariffs, premiums, and contracts aimed to create incentives to innovate. Some efforts were more direct. In the "Report on Manufactures" Hamilton noted that "a society is forming, with a capital which is expected to be extended to at least half a million of dollars." This was the Society for Establishing Useful Manufactures, which Hamilton helped organized to make cotton goods. The state of New Jersey extended tax breaks, eminent domain rights, exemption of its employees from taxes and nonemergency military service, and rights to raise money by lotteries. Most of the society's capital came from federal bonds and stock in the First Bank. Criticized as an unfair competitor because of such benefits, the society failed by 1795. With its failure innovation from above also failed as a general model.[9]

Government production still had sectoral applications. As Hamilton wrote, "It may hereafter deserve legislative consideration, whether manufactories of all the necessary weapons of war ought not to be established, on account of the Government itself." Jefferson, too, had thoughts about a public role in armaments production. As minister to France in 1785, he observed a system of interchangeable-parts firearms used in French musket production, and over the next decade and a half he advocated that the system be adopted in the United States. One respondent was Eli Whitney, who would attempt to introduce uniformity as a firearms contractor.[10]

Scientific knowledge also could revolutionize production. For contemporaries science included any systematic knowledge of the natural world, including applications to production. Americans were deeply engaged in the European Enlightenment, and especially what Joel Mokyr has called the Industrial Enlightenment, which attempted to put systematic knowledge of nature to useful purposes. As a leading exemplar, Benjamin Franklin developed electrical knowledge, invented bifocals, the lightning rod, and the Franklin stove and formed the American Philosophical Society to expand useful knowledge. Americans studied European advances in Diderot's *Encyclopedia* and elsewhere. Scientific societies, colleges, and publications disseminated scientific knowledge. Such knowledge had the potential to transform production, which inventions such as Tom Paine's iron bridge tried to realize.[11] But the potential had limited reality.

Finally, innovation came from below, the product of United States craftsmen and inventors. A few places in the eastern United States had concentrations of craftsmen, including some with mechanical knowledge. In 1791 Wilmington Delaware listed 552 manufacturing workers in 26 occupations. Two occupations processed agricultural goods, 3 made ships, 3 worked metal, 6 worked wood, and 4 made cloth or clothing. Printers and watchmakers added to the range. Providence had similar occupations, with more leather and metalworkers and one fire engine manufacturer. Occupations with knowledge of mechanisms and metalworking, including millwrights, printers, clockmakers, gunsmiths, blacksmiths, and carpenters, played vital roles in early mechanization.[12]

Some inventors succeeded. Eli Whitney, a Connecticut mechanic and Yale graduate, found a simple solution to the pressing problem of ginning short-staple cotton. The cotton gin spread quickly in the South, with little respect for Whitney's patent rights.[13] Jefferson used flour-milling machinery that Oliver Evans invented around 1783, a key invention in milling and in automation more generally. Claiming to double labor productivity, Evans wrote, "These five machines . . . perform every necessary movement of the grain, and meal, from one part of the mill to another, or from one machine to another, through all the various operations from the time the grain is emptied from the wagoner's bag . . . until it be completely manufactured into flour . . . without the aid of manual labour, excepting to set the different machines in motion."[14] After moving to Philadelphia in 1792, Evans constructed mills, produced millstones and plaster of Paris, and in 1795 published *The Young Mill-Wright and Miller's Guide,* which spread knowledge about flour milling, gearing, hydraulics, sawmills, and fulling mills.

Whether initiated from abroad, from above, or from below, innovations were tentative, "precious embryos," limited by inadequate domestic labor supplies, capi-

tal sources, markets, knowledge, and production capabilities. As Whitney and Evans learned, securing returns to patents was challenging; where production was easy, appropriability was not. Such limits shaped the paths through which successful innovations developed and thwarted the development of others.

Diffusing the Industrial Revolution in Textiles

In the United States no less than in Britain, the textile industry was the most visible locus of the Industrial Revolution. Textiles made up about one-third of the value of manufactures listed in the incomplete Census of 1810. In 1831 Rhode Island had 140 cotton mills using 239,000 spindles and 5,900 power looms, and Massachusetts had already eclipsed it. By then the most important cotton textile operations had been mechanized, and domestic technological change was ongoing.[15]

Textile mechanization was a classic example of development from abroad, an aspect of what David Jeremy aptly termed the "Transatlantic Industrial Revolution." Diffusion required profitable usage, a medium to acquire knowledge, and the capacity to use the knowledge. According to Jeremy, Americans followed stages of knowledge transmission, embodiment in a factory, domestic diffusion, and adaptation to U.S. conditions, though the last two stages overlapped.[16] In adapting techniques, the United States went beyond diffusion; development from abroad linked with development from below. Each stage advanced a communications network that came to link hundreds of firms and thousands of individuals. Machinery, technological knowledge, and knowledge-transmitting networks emerged and evolved together. A revolution in technology and organization, the birth of machinists and a textile machinery industry, and ongoing invention were outcomes.

Diffusion is far easier now than in the late eighteenth century. Now pioneering in a country often involves transnational firms importing machinery and personnel to construct and manage a factory. In 1790 pioneers had great difficulty acquiring the technique and then had to learn how to make machinery, organize a factory, and train and manage a labor force. Samuel Slater first successfully solved these problems, and his success formed the basis for others to learn.

News of the British textile revolution spread quickly, and many Europeans and Americans sought to emulate. But diffusion was slow. Buying British machines was rare because their export was prohibited and a British textile machinery industry was just forming. Although it, too, was legally banned, worker mobility was more common, stimulated by the prospect of high income and enabled by recruiting agents and advertisements. Many immigrants were useless; as the proprietor of a Massachusetts start-up declared woefully, "Destitute of the necessary

information ourselves we were subject to be misled by every pretender to knowledge." Slater gained detailed knowledge of techniques and mill organization by superintending the factory of a partner of Richard Arkwright, the key innovator in Britain's factory system. Using his experience in his first tour of Moses Brown's mills, "he declined doing anything with them and proposed Making a New One." Brown acceded, and the partnership of Almy and Brown, made up of Brown's son-in-law and cousin, contracted with Slater "to Direct and Make a Mill in his own way." Slater later became a partner.[17]

Slater's initial task was to design and build workable carding and spinning machinery. Working "with the Necessary Mechanicks Skilled in Working of Wood, Iron, Brass, etc.," Slater took more than a year to construct machinery.[18] Slater was fortunate to settle in a skilled area. One 1796 visitor singled out Pawtucket for its "quantity or variety of manufacturing business." Slater relied on the metalworking skills of the Wilkinson family to make spindles and rollers and the woodworking prowess of Sylvanus Brown for models and frame construction. He ventured into Massachusetts for castings and clothing for his carding machine.[19] Such colonial crafts were essential to the success of mechanized spinning. Cloth continued to be woven in weavers' shops. Almy and Brown provided modest investment. When its plant was completed in 1793, Almy and Brown had given textile production a British form: a partnership between business acquaintances, friends, or family members running a waterpowered spinning mill employing women and children to spin and machinists to maintain machinery.

The firm succeeded. Under Slater's management annual expenses grew from $1,600 in 1793 to $20,400 in 1803. Accumulated profits through 1803 amounted to $18,000. The substantial investment in developing the system was warranted by the large output of low-cost goods. As Moses Brown put it, "When Each Branch is Learned it may be Extended to Any length Necessary by Means of the great Advantage of the Mashines and the saving of Labour."[20] Almy and Brown manufactured nearly 8,000 yards of cloth in the 10 months after the factory was in operation. Over the decade improved processes and inputs deepened the advantages. Slater triumphed so quickly by minimizing departures from Arkwright's techniques and organization. Others, including Hamilton's Society for Establishing Useful Manufactures, failed in attempts at more basic changes. Little benefit came from above. Almy, Brown, and Slater received no subsidies, and science played little role. The critical technologies were not patented; Slater's sole patent came in 1825.

Factory textile production spread little for a decade. Many tried to enter but floundered, failing to acquire funding, practical machinery, and labor or to compete with rising British imports after 1793. Technological knowledge was clearly not

a pure public good, freely available to all. Success required hands-on knowledge of the design, production, maintenance, and operation of machinery. Because such knowledge was not easily codified, first movers had a big advantage.[21]

Slater, his partners, and his workers led domestic diffusion. Detailed descriptions of textile machines, published from about 1820, were insufficient to begin production. Almy, Brown, and Slater could more easily set up a second plant than others could at first, so they, like Arkwright in Britain, formed new partnerships. Around 1800 Almy and Brown established one new factory and Slater another. In the next eight years they led industrial expansion around Providence. In 1808 Almy, Brown, or Slater owned eight of the 26 mills within 30 miles of Providence. Five former Slater employees equipped nearby mills, so that the original partners and their employees formed 11 of the 16 mills running over 500 spindles in 1808. Other employees took Slater technology to Philadelphia and to towns in Massachusetts, New Hampshire, and New York. Slater, Brown, and Almy added partnerships after 1810. By the time of his death in 1835 Slater had formed a dozen textile firms as well as a foundry and a machine shop.[22]

Other firms soon accounted for the bulk of textile expansion.[23] Slater's workers transferred techniques, as did his workers' workers. British textile managers and machinists added to the skill base, including 34 textile machinists immigrating from 1809 through 1813 and another 153 from 1824 through 1831. The Embargo, War of 1812, and resulting import barriers led to massive entry and a 50-fold explosion of New England cloth production from 1805 to 1815. Postwar British imports slowed entry but did not stop it; Americans had acquired sufficient technological prowess to compete, probably aided by tariffs. Growth in the 1820s was great.[24]

U.S. firms spread machinery to weaving. To reduce costs and overcome the need to put out weaving up to 100 miles away, firms copied and improved imperfect British machines. Two efforts succeeded. The more revolutionary among them formed a wholly new system that combined the power loom, corporate organization, large investments, integrated spinning and weaving, and a new source of labor. It began in 1811, when the wealthy Boston merchant Francis Lowell studied Glasgow and Manchester factories. In 1813 he used subscriptions of $100,000 to form a Massachusetts corporation, the Boston Manufacturing Company, which built a factory in Waltham. Lowell designed a mechanically simple loom and purchased, copied, or developed auxiliary equipment. His success rested on the simplicity of his techniques, which could make a single kind of low-quality product yet one that was adequate for mass markets and easier to introduce. It also rested the ability of Paul Moody and other machinists hired to develop and make his machines. Employing young New England women as operatives, along with carpenters, smiths, and oth-

ers in the machine shop, the firm's success was quick. Waltham's annual revenues jumped from $24,000 in 1816 to $261,000 in 1820. From 1817 through 1826 dividends averaged almost 19 percent annually.[25]

The Lowell system grew quickly. Boston Manufacturing quadrupled its capitalization. From 1822 new capital-intensive corporations, largely owned by the same Boston financiers, spread the system to East Chemsford (renamed Lowell). By 1834 10 Lowell companies had 19 mills operating 110,000 spindles and authorized capital of almost $7 million. With low unit costs Boston Manufacturing enjoyed high profits after the War of 1812, when British imports bankrupted others. Lowell firms had longer production runs, higher capitalization, three to four times as many spindles per mill in 1831, and advantages of greater vertical integration and internal coordination.[26]

Other firms adopted the power loom of William Gilmour, who brought plans from Scotland. Helped by Providence mechanics, he brought it to practicality and received $1,500 from appreciative Providence manufacturers. Superior in principle, it wove finer, higher-quality cloth but was more complex and harder to operate. It gained wide use in southern New England and the Middle States from the 1810s, when Slater and others set up integrated spinning and weaving factories. Its users were typically partnerships, smaller and less capital-intensive than Lowell firms, and relied more on child labor. They had shorter runs of cloth and made a wider range of textiles. Integrated firms averaged $39,900 in capital in 1820, compared to $17,600 for firms that only spun. Partly because of the heterogeneity of firms and products outside the Lowell system, the Gilmour (or Scotch) loom spread more slowly, and handloom weavers persisted well into the century.[27]

By 1830 cotton textile factories with power spinning and weaving were typical in New England, though less so elsewhere. Spinning capacity increased greatly from the Embargo. Approaching 100,000 in 1810, installed spindles tripled in the next decade in the face of postwar imports and then quadrupled through 1831. Factory cloth output grew even faster, surpassing 200 million yards in 1831, led by New England. As factories rose, home production for subsistence and sale declined. By the mid-1830s factories dominated cotton textile production, especially in the coarse goods used by most families.[28] Here was an economic transformation of the first magnitude.

The birth of the factory was tied to the origin of machine-making methods. Making and using textile machines were very different processes. Machinists had to design and produce parts out of metal and wood, whereas operatives needed little design skill and worked with wool and cotton. Textile mills operated on a large scale, using as many as 5,000 spindles in the 1820s to make a million yards of

cloth, a far cry from the few machine tools and files that filled custom machine orders. Slater found no machinists when he came to the United States for the simple reason that there were none. Millwrights used mechanical knowledge to make and operate waterwheels, gearing, and milling equipment, but textile machines differed basically in design, complexity, accuracy, and production requirements. And just as new textile techniques came with the factory and the industrial firm, so textile machinery came with the machinist and the textile machinery firm.

Slater's principal metalworking contractors, Oziel Wilkinson and his son David, illustrate how a craft economy met conditions for mechanization. Oziel was a blacksmith whose products ranged from scythes to nails to anchors. In the late 1780s he bought machinery for making heavy screws used in paper manufacture, clothiers' presses, and oil mills, and David molded and finished the screws. In the mid-1780s the shop was drawn into the first wave of textile mechanization. Before Slater arrived, the Wilkinsons filled 12 orders for Almy and Brown in 1789, including 100 jenny spindles, parts of carding machines, and 18 sets of screws and nuts. They then worked with Slater to forge and turn spindles and rollers. The forge-and-file techniques of the blacksmith were primitive; Wilkinson stated that "all the turning of the iron for the first cotton machinery built by Mr. Slater was done with hand chisels or tools in lathes turned by cranks with hand power."[29] In textiles, as elsewhere, craft metalworkers, carpenters, and millwrights were vital to mechanization.

One reason firms took so long to follow Almy and Brown was the limited knowledge of machine design and production. The Wilkinsons helped overcome this limit. Over the 1790s Oziel set up a reverberatory furnace and a rolling mill, enabling him to make whole machines. In 1800 he, Slater, and two others set up a textile mill. David proved more important. In 1800 he built a machine shop that operated for three decades, which made textile machinery, mill shafting, gearing, steam engines, large screws, waterwheel governors, cannons, nails, and parts for canals and bridges. He trained many machinists, who often formed their own shops, and interacted widely with textile machinists. He held interests in textile mills and, with Slater and others, set up the Providence Iron Foundry in 1817. He invented a screw-making lathe that copied a lead screw, which he modified into a slide lathe, the basis of the engine (or industrial) lathe central to modern metalworking. He also invented and improved textile machinery.[30] While Slater led in developing the textile factory, Wilkinson led in making textile machines, with much significance for wider mechanization.

Textile firms acquired machinists' skills in three ways: by forming partnerships (such as those involving both Wilkinsons), by hiring machinists to build and maintain the mill's machine shop and machinery, and by purchasing equipment and

installation services from textile machinery firms. Over time firms came to purchase new machinery and employ machinists to maintain it. The transition was well under way by the 1830s, and David Wilkinson led it. Using superior machine tools and metalworking skills, he sold to numerous Rhode Island and Massachusetts establishments and to firms in nine other states, from Vermont to Georgia. He refined designs and production techniques to make and sell practical spinning machines. He pioneered the sale of power looms, building looms from Gilmour's patterns and helping bring the loom to practicality. He also built machine tools. Around 1807 he built a slide lathe for a Pomfret, Connecticut, textile firm in which he was an owner and sold use of his patterns to construct a lathe for a Rhode Island mill.[31] Wilkinson could achieve such success in a period when both machine making and machine using were in their infancy because he was positioned at the juncture of leadership in textiles and metalworking.

Just as Slater's success led to emulation, so did Wilkinson's. He originated a lineage of machinists who widely diffused machines and the knowledge and practices of machine making (fig. 2.1). Wilkinson worked with Alfred Jenks to build Slater's machinery; Jenks took copies of machine drawings to Philadelphia, where he formed its leading textile machinery firm. Most stayed nearer home. Trained as a patternmaker by his father, who made patterns for Slater's first machines, James S. Brown worked for Wilkinson in 1817 and two years later for another Pawtucket textile machinery firm, Pitcher and Gay. He became Pitcher's partner, took over the firm in 1842, and developed self-acting mules and improved lathes. From a family associated with a small cotton mill in Taunton, Massachusetts, Jonathan Lincoln apprenticed as a machinist before working for Wilkinson around 1825. Here he learned to make spinning and weaving machines, waterpower and gearing equipment, and machine tools. In 1829 he moved to the emerging center of Fall River, where he built textile machinery and later turbines.

Wilkinson's associates also trained textile machinists. Slater's workers equipped factories in several states. Larned Pitcher set up a textile machine shop around 1813 and a partnership with Ira Gay in 1819, which employed Aza Arnold, James S. Brown, Merrill Furbush, and Thomas Hill. Arnold made machines in New Hampshire mills, opened a machine shop in North Providence, traveled among textile towns, invented, and ran a Philadelphia printworks. In 1834 Slater and Thomas Hill formed the Providence Machine Company, a major textile machinery firm. Furbush organized loom works in Worcester and Philadelphia. Pitcher, Gay, Slater, and others built a mill in what became Manchester, which helped originate Amoskeag, the largest textile mill in the country. Gay then made machines for the Nashua Manufacturing Company and formed Gay and Silver in

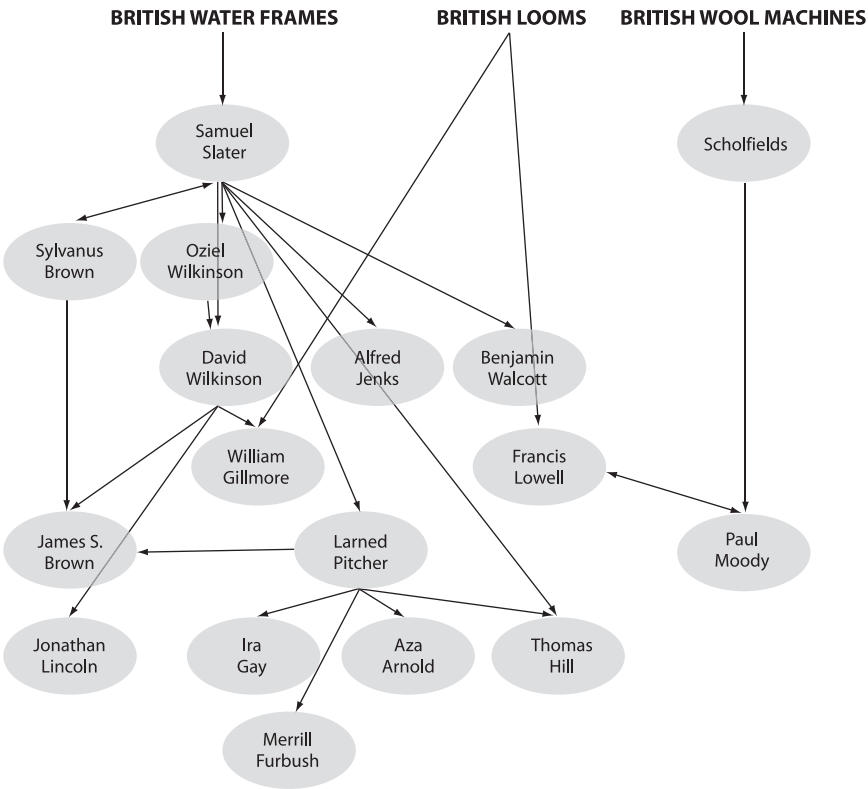

Fig. 2.1. Lineages of textile machinists. *Sources*: Joseph W. Roe, *English and American Tool Builders* (New Haven, Conn.: Yale Univ. Press, 1916); Kilburn, Lincoln Machine Co., Business Records, 1835–1929 (Baker Library, Harvard Business School, Boston); Jonathan Thayer Lincoln, "Material for a History of American Textile Machinery: The Kilburn-Lincoln Papers," *Journal of Economic and Business History* 4 (February 1932): 259–80; J. Leander Bishop, *A History of American Manufactures from 1608 to 1860*, vol. 3 (Philadelphia: E. Young, 1868); *Dictionary of American Biography*.

North Chelmsford, Massachusetts, significant for its machines and its machinists. Other centers developed in Paterson, Philadelphia, and Matteawan, New York. By 1835 textile machinery networks had spread far beyond Slater and Wilkinson.[32]

The Lowell system formed another center. Needing mechanics to perfect and make his machinery, Francis Lowell unsuccessfully sought Jacob Perkins, a leading metalworker and inventor of important nail-making machines. Lowell then hired Paul Moody, who had worked with the Scholfields, leading wool machinery producers. Moody constructed and superintended the Waltham machine shop. Benefiting from recent progress, he purchased metal- and woodworking machinery,

unlike the Wilkinsons a generation earlier. Moody proved essential to completing a system of machinery by 1818. Among the firms the Boston Associates set up, the Proprietors of the Locks and Canals on the Merrimack River made, sold, and installed machinery and waterpower for the Lowell mills and occasionally for others. Machinists frequently moved among Lowell firms.[33]

By the mid-1830s well-structured networks linked the activities of textile firms, textile machinists, and textile machinery firms. Networks communicated new knowledge most readily gained on the job, including knowledge of technology and of opportunities in other firms and areas. Machinery firms were at the center of networks because they sold to many firms. Machinists' mobility between firms, into new partnerships, and across space transmitted knowledge among mills and machinery firms. Proprietors, managers, and workers in textile firms also spread knowledge, though for "factory hands," as the census listed them, it was typically about how to operate the machines. The density of contact was greatest in centers of textile production such as Providence but also united cities with areas around them, such as those among which Ira Gay moved. Machinists' mobility extended across regions, uniting textile regions of New England and the Middle States.[34]

Textile machinery firms originated from mills and earlier machinery firms, augmented by generic machine shops and metalworking firms. A few were large, such as Locks and Canals, which in 1831 employed 200 workers and was capitalized at $600,000. Most were small; in 1831 two-thirds of Massachusetts firms invested $6,000 or less in machinery and buildings, and half of them employed 15 or fewer workers. Most purchased castings from foundries. The growing numbers of textile machinists overcame a constraint on industry growth. Early firms had to develop their own machinery skills, which slowed expansion. This constraint continued as output exploded. By the 1830s sufficient numbers of machinists and machinery firms existed to overcome the bottleneck.[35]

Machine tools and foundries became essential in making textile machinery. Inventories document the penetration of machine tools. Wilkinson's initial equipment was rudimentary. In 1817 Boston Manufacturing used eight lathes and several more specialized machines, along with files, vices, anvils, and carpenter's tools. In 1834 Otis Pettee's shop, located down the Charles River from Waltham, used 40 hand lathes, 8 engine lathes with iron frames of various sizes, 2 engine lathes with wooden frames, 3 drilling machines, several boring machines, a gear cutter, 2 waterwheels, and 2 steam engines.[36] Still fundamentally dependent on handwork—imported British files were common in 1831—machinery firms used machines to make machines.

Records of the Providence Iron Foundry, formed by Slater, Wilkinson, and Hill in 1817, document the region's casting needs. The firm concentrated on parts for

looms and other textile machines. Its ledger from 1817 through 1823 listed about 500 accounts, mostly customers but a few employees or suppliers. It cast and sometimes finished parts, mostly generic parts such as pulleys, couplings, shafting, and many kinds of wheels. Customers' own machinists typically, but not always, installed the castings. It sold to many Slater mills; machinery firms including Wilkinson, Pitcher, James S. Brown, and Aza Arnold; and inventors such as John Thorp and William Gilmour. Some customers had dozens of orders. The biggest, Wilkinson, had accounts totaling over $10,000, which, at rates of five cents per pound, constituted over 200,000 pounds of castings. Patterns were essential; order books contain frequent discussions about who furnished patterns and how they were to be kept. One firm sent a pattern and, expecting repeat business, wrote: "Keep the pattern. Call it Womick loom Beam Head pattern." After 1829, when Wilkinson left the area, the firm added a few whole machines to its casting orders, including a doubler, a lapper, speeders, and a lathe.[37]

The textile machinery industry expanded rapidly, probably faster than the 15 percent annual growth of the cotton textile industry because more operations were mechanized and machine production moved into independent shops. The Census of 1810 listed 12 shops, all in Rhode Island, at a time when textile machines were mostly built in the mills using them. The Census of 1820 underreported machinery firms, but 28 carpenter shops all over the country made spinning wheels. By the 1830s household spinning was in decline and with it spinning wheel output. Incomplete for much of the country, the McLane Report surveyed Massachusetts thoroughly in 1831 and listed 34 shops making textile equipment employing 819 workers. Some made auxiliary products such as shuttles and bobbins, but 23 shops with 671 workers made textile machines; Locks and Canals stated it could make 15,000 spindles annually.[38] Mills added to the number of machinists. By 1835 textile machinists and the textile machinery industry structured the expansion of factory production. Machinery purchases sped diffusion, increased machine quality, and reduced the demands on mill machine shops. The well-formed northeastern market for textile machinists relaxed knowledge constraints for new entrants.

As machinists diffused techniques, they also invented. Domestic invention was more a complement to international diffusion than a substitute. Invention need not accompany diffusion, as the modern turnkey factory exemplifies, but Americans had ample incentives and capabilities to invent. Inventors sought to benefit by making textiles, making capital goods, or selling patent rights. Growing factory output increased the potential market for improvements. This demand side determinant was accompanied by supply side factors. Successful invention

required the capability to identify, conceive, and solve technological problems. This capability had universal and industry-specific components. Inventors benefited from knowledge of mechanical principles, experience in visualizing technical problems and depicting visualizations in drawings, and the capacity to build and test models, factors that pertained to all types of machinery. Knowledge of textile technology narrowed the group best positioned to invent. As textile machines became more complex, inventors knowing factory techniques more readily identified problems and formulated solutions. Textile machinists and mill superintendents brought together generic and specific knowledge. Publications and patent specifications also spread technical knowledge, especially after 1820, but the information was too incomplete to substitute for involvement in the industry.

The embeddedness of knowledge provided advantages to industry practitioners and hence affected who invented. It directed inventive effort to pressing problems. Consider carding. Both mechanized and hand carding used card clothing, which was a surface of leather with bent wires inserted. Oliver Evans and others developed wire-cutting and bending machines to shape card teeth, which were inserted by hand. One Boston shop employed hundreds of workers inserting the teeth. Carding practitioners tried to mechanize the process, led by Amos Whittemore, a gunsmith and a partner in a carding firm George Washington visited in the 1790s. In 1797 he patented a machine that automated each step, from making and bending teeth to pricking leather, inserting teeth, and making a final bend in the wire. His invention emerged from his card-making experience and (as a lawsuit claimed) from the invention of others inside and outside his firm. In 1809 the Whittemores used 37 machines to make hand cards and card clothing valued at $100,000 annually. Factory carding used different card-clothing shapes, including Slater's narrow endless-belt clothing for carding machines. In 1803 Pliny Earle, a Leicester, Massachusetts, card maker who provided early help to Slater, invented a machine to make machine card clothing, which proved so successful that he was contesting five infringement suits in 1815. Others developed larger, more refined machines. By then technological change had become a cumulative process in which inventions built on other inventions.[39]

Patents document the evolution of textile techniques. Patents were an imperfect measure of inventive activity, much less inventive success, for some inventions were not patented and patents differed greatly in quality. But for textiles they were not a bad measure because almost all major U.S. textile inventions were patented and the rationale for patenting strengthened as sale of patent rights was regularized.[40] In a sample of 390 textile patents, patenting grew enormously after 1805, paralleling factory expansion. Sampled patents increased from 0.8 annually before 1805 to 11.7

in the following decade, when factory production was stimulated by the Embargo and the War of 1812. As British imports renewed after 1815, annual textile patents declined to 8.9 through 1825, but peaked at 17.2 in the 1826–35 decade.[41] Carding was especially important before 1815, power looms in the 1806–15 upsurge, and spinning inventions in the 1820s and 1830s.[42] Inventions used in the home declined, including spinning wheels and handlooms. Averaging 9 percent of all patents over the whole period, they fell to 4 percent in the last decade. Jefferson's image of homes using jennies and handlooms to make their own cloth was not to be.

If invention was based in textile networks, it should have been concentrated near factories. By 1831 about 70 percent of cotton textile production was located in New England, though woolens were more dispersed. The textile machinery industry located in the same region. New England inventors received over half of all patents (table 2.1). The Middle States followed in both factory production and invention. The rest of the country had less than 10 percent of all patents. Inventors located similarly. The 48 percent of inventors in New England was nearly three times its 1820 population share. Inventors overwhelmingly took out a single textile patent; inventing was more a complement to other activities than a profession in itself. Repeat inventors averaged 3.4 patents in New England, above other regions, due in part to synergies with textile and machinery firms. As a result, New England had three times as many patents per capita as the national average. By contrast, the South had 11 percent of the national average and the West 54 percent. Within regions patenting located near production. The Providence area was the largest inventing center, with one-tenth of textile patents locally and one-quarter within a 30-mile radius. Only one-fifth of inventors were located in cities, led by Providence, but many others were located in textile towns.

Inventors often came from occupations with mechanical skill and linkages to textiles. Occupations have been identified for 52 inventors, all but 2 from city directories, totaling one-sixth of all patentees with a quarter of sampled patents. Three-fifths were machinists, and among this group three-quarters made textile machinery. One-fifth had other manufacturing professions; seven owned or managed textile mills, some, including Francis Lowell, with mechanical training. Machinists led in repeat invention. The three-eighths who produced repeat inventions averaged 4.8 textile patents, far above any other occupation. As a result, machinists received three-quarters of the patents of those with known occupations.

Inventors within innovating textile networks—mill managers, textile workers, and textile machinists—constituted three-fifths of all inventors. The share may have been higher because textile machinists who listed their occupations simply as machinists were not included.[43] Three-quarters of network inventors were machinists,

Table 2.1. Textile Patentees, 1790–1835

	Inventors	Inventor Share (%)	Average Patents	Repeat Inventor Share (%)	Average Patents, Repeat Inventor	Patent Share (%)	Patents per Capita Index
All	298	—	1.31	16.4	2.88	—	—
New England	138	47.6	1.43	18.1	3.36	51.6	3.05
Mid-Atlantic	121	41.7	1.24	16.5	2.45	39.3	1.20
South	14	4.8	1.21	21.4	2.00	4.5	0.11
West	17	5.9	1.06	5.9	2.00	4.7	0.54
Urban	57	19.7	1.63	26.3	3.40	24.3	5.46
Machinists	31	59.6	2.45	38.7	4.75	76.8	—
Science and invention	1	1.9	1.00	0	—	1.0	—
Other manufacturing	10	19.2	1.00	0	—	10.1	—
Trade and services	10	19.2	1.80	30.0	3.67	18.2	—
Network	31	62.0	2.26	32.3	4.90	70.7	—
Nonnetwork	19	38.0	1.53	26.3	3.00	29.3	—

Sources: Edmund Burke, *List of Patents for Inventions and Designs, Issued by the United States, from 1790 to 1847* (Washington, D.C.: J. & G. S. Gideon, 1847); U.S. Patent Office, *Subject Matter Index of Patents for Inventions Issued by the United States Patent Office from 1790 to 1873, Inclusive* (Washington, D.C.: Government Printing Office, 1874); various city directories. Population from U.S. Department of State, *Census of the United States (1820). Census for 1820* (Washington, D.C.: Gales & Seaton, 1821).

Note: Cotton and wool textile machine patents were taken from a cumulative list of all U.S. patents through 1873 and checked against another list in 1846. The Mid-Atlantic States include Delaware, Maryland, New Jersey, New York, Pennsylvania, and Washington, D.C. Regional divisions omit two foreign patentees and six without residence. Urban inventors received at least one textile patent in a city with 10,000 population in 1820. Two inventors with occupations determined from census manuscripts were excluded from network comparisons. The patents per capita index is the region's share of total patents relative to its 1820 population share (so that the index for the United States would be 1.0).

usually in machinery firms. Network inventors received 70 percent of patents. A larger share had repeat inventions, and those who did averaged more patents. Who secured usage is not known, but the 15 percent of inventors who owned or superintended textile machinery or textile firms or who licensed patent rights to such firms were positioned to gain use. They averaged 2.2 textile patents, compared to 1.2 for others.[44] Three-eighths of such inventors had multiple patents; Paul Moody, John Thorp, and the important wool textile inventor John Goulding each received five or more. Knowledge of mechanical principles was most useful when combined with knowledge of textiles and the position to bring patents into use.[45]

Just as growing factory production supported invention, invention advanced factory production. Machine carding and machine-made card clothing greatly reduced carding costs. In this regard the United States led Britain, which still largely

made card clothing by hand. Power looms extended factory production in coarse and finer cloths. Ira Draper's self-acting temples improved loom functioning. Britain's lead was greatest in spinning, but U.S. improvements began to close the gap. The most original was the differential gear that Aza Arnold invented for roving frames, which prepared cotton for spinning. By solving the problem of varying the relative speed of the bobbin and spindles to slow bobbin rotation as the bobbin filled, it reduced thread breakage and improved flexibility in changing the fineness of work. As a British textile expert stated in 1836, "The good yarn formerly made, required prodigious pains in the first adjustment of the machine; and its quality could not be altered to suit a new market without extraordinary exertions."[46] Without such domestic inventions the textile industry would have developed more slowly.

New methods to make and power textile machines had the same effect. Wilkinson's lathe produced more precise machines. Paul Moody substituted leather belts for metal gearing in the main shafts running from the waterwheels. This innovation, begun in Lowell in 1828, initiated "a new American style which soon came to constitute an important distinction between English and American mills." Belting overcame metalworking deficiencies in gear making and was quieter, more durable, less costly, and enabled higher running speeds for machines. Led by Lowell, mills utilized more efficient waterwheels and water-flow methods. Steam engines gained some usage in urban mills, including Slater's Providence Steam Mill, and supplemented waterpower in others.[47]

By the mid-1830s textiles had acquired a dynamic of ongoing invention, largely undertaken by network practitioners and communicated through network channels. Machinists and machinery firms were especially important because they combined universal knowledge of machinery and particular knowledge of textiles. Interactions among machinists perfected inventions, including the roving frame, which Aza Arnold discussed with Wilkinson, Gay, and Pitcher.[48] Superior products offered competitive advantages to existing textile machinery firms and incentives to form new ones.

Invention, output growth, and knowledge expansion had come to form a positive feedback system. As textile and textile machinery output grew, so did textile machinery knowledge and the ranks of machinists, which added density to machinists' networks. Growth supplied inventive incentives, and added knowledge provided the means. Invention in turn increased output growth. Organizational innovations, especially the birth of integrated textile mills and textile machinery firms, led to faster and wider learning. Such feedbacks had little reality through 1805, when diffusion was limited. After 1805 diffusion increased and invention lowered costs and extended the range of mechanization. The limited supply of machin-

ists impeded growth, but training in mills and textile machinery firms relaxed the constraint and extended machinists' networks. The path of mechanization had a momentum that could not help but affect later textile development.

Adapting the Industrial Revolution: Steam Power

In 1786, when he was minister to France, Jefferson visited a British flour mill powered by James Watt's newly perfected steam engine. Much impressed, Jefferson noted that "it is simple, great, and likely to have extensive consequences." It will "lay open all the streams for navigation," promoting commerce and binding the nation together. The engine "will be applied generally to machines," replacing waterpower.[49] Jefferson's expectations were on the mark. By the 1830s the steamboat had transformed river transportation, and engines powered machines for many uses. A dynamic had begun that would spread steam power across industry and transportation. As Jefferson would have applauded, the rise of U.S. steam engineering rested not simply on diffusion but also on American invention. The question is how a relatively backward country, rich in waterpower but poor in machine-making capabilities, could spread and transform a machine of such universal importance.

To introduce the steam engine was no easy task. The practicality conditions—that the engine, boiler, and gearing functioned effectively, durably, and more efficiently than other energy sources—imposed design and production requirements that the early Republic, with virtually no machinists, could not readily meet. In spite of the obstacles, the strong interest in engines spawned four American beginnings. As in England, the Newcomen engine was first, used commercially as a pump to remove water from mines. Only three such engines were used in the United States. The second was the steamboat clamor from the mid-1780s. John Fitch and James Rumsey, learning from Newcomen and Watt engines, patented and built steamboats that traveled upstream by mechanical power. Lacking adequate engine designs, propelling mechanisms, and construction methods, they and a half-dozen other steamboat inventors before 1807 all failed. The third beginning spread the Watt engine. In 1801 Benjamin Latrobe, an émigré British engineer and architect, built two pumping engines for the Philadelphia waterworks with the help of two former Boulton and Watt employees. The engine's fitful performance resulted from weak U.S. iron-working capabilities, so poor that boilers were made from wood. Others emulated Latrobe, including the Manhattan Water Company, which imported the first Boulton and Watt engine in 1804.[50]

The fourth beginning rejected diffusion. After 15 years of steam experimentation, the flour mill inventor Oliver Evans focused on the steam engine in earnest

around 1801. He felt that Watt's low-pressure engine underutilized the potential of steam because its power came from the pressure difference between the atmosphere and the partial vacuum created by rapidly cooling steam, which "pulled" the piston. His machine used steam pressures up to 10 times that of the atmosphere to "push" the piston. Because the pressure on the piston was so much higher, a high-pressure engine of the same cylinder size and stroke rate could generate far more power.[51]

Even the best expert could not predict which beginning would succeed. In an 1804 report Latrobe identified five functioning steam engines in the United States, two in his waterworks. Noting Evans's efforts in passing, he recommended low-pressure engines and disparagingly rejected America's "mania . . . for impelling boats by steam-engines." American innovations seemed unpromising.[52] One might conclude that the United States would adopt British low-pressure engines to pump water and move machinery. Latrobe's judgment proved fundamentally wrong; the high-pressure engine and the steamboat soon flourished, led by American innovations.

Practical stationary engines and steamboats emerged by 1812. Evans led the former process. His 1804 patent recognized the engine's universality: "I mean to apply my steam engines to move all kinds of machinery to grind, saw, pump, forge, roll, slit, turn stone, plane, etc. etc., to move forge and furnace bellows, to propell boats, and land carriages."[53] But how was such usage to be gained? Evans's answer presaged a dominant industry pattern: design practical machines, translate the design into durable products, and sell them as capital goods.

The author of the nation's most widely read mechanical engineering text, Evans was well placed to pose and solve mechanical problems. His steam engineering interests had already led to a 1787 Maryland patent. He initially tried to use steam pressure to generate rotary motion directly, similar to a rotating lawn sprinkler. The rotary principle generated too little power, so he turned to a reciprocating engine. His 1801 engine, with a small cylinder and no condenser, was much simpler than the Watt engine. Evans then improved the valves admitting steam into the cylinder, designed a better boiler, and developed means to convert reciprocating into rotary motion. His Columbian engine of 1812 marked the engine's practicality. He also invented steam-driven machinery, including a grinding mill and a patented sawmill.[54]

Finding workable production methods was a challenge. Fitch's steamboat failed partly because he could not make iron boilers. In 1800 makeshift machines took 87 days to bore a half-inch of a cylinder for Philadelphia waterworks. Evans's first machine, combining thin copper cylinders and a partly wooden boiler, was insufficiently durable. Evans built the Mars Works to remedy the defect. An 1808

advertisement described the plant: "MARS WORKS . . . consists of—1st. An Iron Foundery—2d. A Shop for making such patterns as may be ordered—3d. Blacksmith's Shop——4th. Steam mill for turning and boring heavy iron and grinding plaster—5th. Steam Engineer's Shop."[55] This plant and his Pittsburgh Steam Engine Factory, built in 1812, made engines and related machinery. The foundry cast parts that were then bored and turned. Malleable iron parts were forged by hand. Engines were then assembled and adjusted. Evans's equipment likely mirrored that of Robert Fulton's Pittsburgh plant in 1813, which included three lathes in what was revealingly called the "filer's shop." Evans's engine drove machinery, but handwork dominated.[56] Boring mills were more primitive than those used in Britain. Lathes cut only roughly. The iron-planer did not yet exist. The file, chisel, foundry, and forge compensated, but accuracy was a certain casualty, contributing to the short life span of engines, typically only a few years. Evans's simple engine design and narrow cylinder minimized the production problems, although the boiler remained troublesome because high pressures caused serious accidents, especially on steamboats. Like Lowell's mechanically crude textile equipment, Evans's engine had the advantage that it was simpler to construct, alleviating obstacles due to weak production skills.

Considerable exploration underlay Evans's decision to make and sell engines and related products. He decided not to rely on selling or licensing patent rights. His efforts to license flour-milling patents had been frustrating, though royalties partly funded engine development. Evans insisted that only by manufacturing did he benefit from his invention. He could have integrated engine making and engine using. He did build a steam-powered flour mill. But recognizing that his real advantage lay in engine making, he concentrated on machinery. He accompanied his engines with boilers, gearing, and power-driven machinery, which used his plant more fully and ensured quality and compatibility of the engine and the machines it drove. Evans made equipment to roll iron, press sugarcane, grind plaster, make paper, and mill flour. He also undertook casting, forging, and machining work, particularly that requiring subtle design or implementation.[57] His customers were mostly local and regional, so his workers could compensate for users' limited knowledge of steam mill construction and usage.

The combination of intimate knowledge of the core invention, design abilities to adapt it to customers' needs, and production capabilities led to Evans's belated prosperity. In 1812 he reported 10 machines in use sawing lumber, milling flour, turning metal, running a woolen mill, drawing wire, grinding glass, and making steam engines, and 10 more ready to install.[58] The Mars Works employed 35 workers and was constantly on the lookout for others. One ad seeking "young mill-

wrights" stated that they will "be instructed in the art of making Steam Engines, building Steam Mills and attending them, and when capable, they will have opportunities of going out with steam Engines, to build Steam Mills, and to instruct others to keep them in repair, and attend them, for which they will be paid very high wages."[59]

Steamboats first succeeded in the 1807 voyage of Robert Fulton's *Clermont* (then called the *North River Steamboat*). Science was an essential input. As his 1809 patent stated, he designed a ship with appropriate relations of drag (resistance to movement through water), engine power, and paddlewheel size and velocity. Fulton's design utilized existing theory, systematic empirical studies, and his own experiments. He was not always right—his first French boat sank under the engine's weight, and the dangerously narrow *Clermont* had to be almost doubled in width—but his systematic understanding allowed him to learn from mistakes.

Fulton left Philadelphia for England to become an artist but, failing to do so, turned to engineering. He met Rumsey, who was seeking Boulton and Watt's support. Fulton became a canal engineer, published a book on the topic, and circulated widely in the scientific and engineering community. Interested in submarine warfare, he went to France, where he met Robert Livingston, a New York landowner, minister to France, and unsuccessful steamboat inventor. Concentrating on steamboat invention from 1802, Fulton studied American and European efforts, corresponded with English inventors and with Boulton and Watt, and studied the literature on water resistance and boat design. His engineering experience and acumen, wide knowledge and contacts, and an export license for a Boulton and Watt engine advanced his invention. Fulton turned homeward when Napoleon and the British government rejected his submarines and when Livingston's political contacts secured them a steamboat monopoly in New York State if their boat could average four miles per hour.

The voyage of the *Clermont* from New York to Albany initiated a revolution in water transportation. Over time Fulton added width, strength, and better power transmission to improve stability, durability, and efficiency. He identified passenger service as the key market and designed New York ferries. The Watt engine eased initial production problems. Fulton learned enough from its use to have others made domestically, contracting with Robert McQueen of New York for iron castings and the engine maker James Allaire for brass castings. He set up an extensive shop in Jersey City and made five engines and machinery for four boats in 1812. With practical boats and a boating monopoly, Fulton and Livingston prospered, increasing their fleet to 21 by 1815.[60]

How did Evans and Fulton surmount barriers from limited knowledge and skills? Patenting and monopolies improved prospects if they could design practical machines. Both had invented earlier, which helped them pose and solve technological problems. Steam power was a common part of books about "natural philosophy," which discussed (if incompletely) engine design and relations of temperature, pressure, and power. Colleges, scientific organizations, and informal communication also spread knowledge. Fulton learned from the scientific community in England, including the physicist John Dalton. Philadelphia was a lesser center, but Evans consulted with Robert Patterson, a mathematics professor at the University of Pennsylvania and later the director of the U.S. mint and president of the American Philosophical Society. Engine inventors linked with the emerging scientific community much more fully than did early textile inventors.[61]

Science was not enough; Evans and Fulton relied on an emerging community of steam engineering practitioners. Carroll Pursell pointed to "the vital importance for steam engineering in early America of the cross-fertilization of efforts through frequent interchange of men, inspiration, and ideas." The process began with Newcomen engines. Josiah Hornblower, whose engineer father was an associate of Newcomen, built the first for a New Jersey copper mine (fig. 2.2). The Irish immigrant Chrisopher Colles built the second one in New York; Peter Curtenius cast its cylinder and consulted in building another in Rhode Island. Nicholas Roosevelt leased the New Jersey copper mine and hired Hornblower to repair its engine. In the second half of the 1790s Roosevelt hired James Smallman, Charles Stoudinger, and Lewis Rhode to construct Latrobe's waterwork engines. Smallman became an important engine builder, and Stoudinger worked for Robert Fulton on the first successful steamship line. Rhode trained James Allaire, a Fulton contractor who became a major engine builder. In 1798 Roosevelt built steamboats with John Stevens and Robert Livingston. Stevens knew important inventors from Fitch to Fulton and Evans.[62]

These emergent networks shaped the path to practical engines. Hardly a freely available public good, knowledge of engines and their application was embedded in scientific and practical networks, and access to this knowledge shaped who invented. Innovations were highly uncertain. Watt doubted the viability of steam locomotion, market size was unclear, and in the absence of a machinery sector production methods were primitive. Uncertainty gave innovation paths an exploratory character, and successful searches brought emulators. Evans and Fulton succeeded, while others failed.[63] They developed major new product designs, found and utilized metalworking skills to translate designs into reality, built two of the country's most advanced metalworking shops, and found markets for ma-

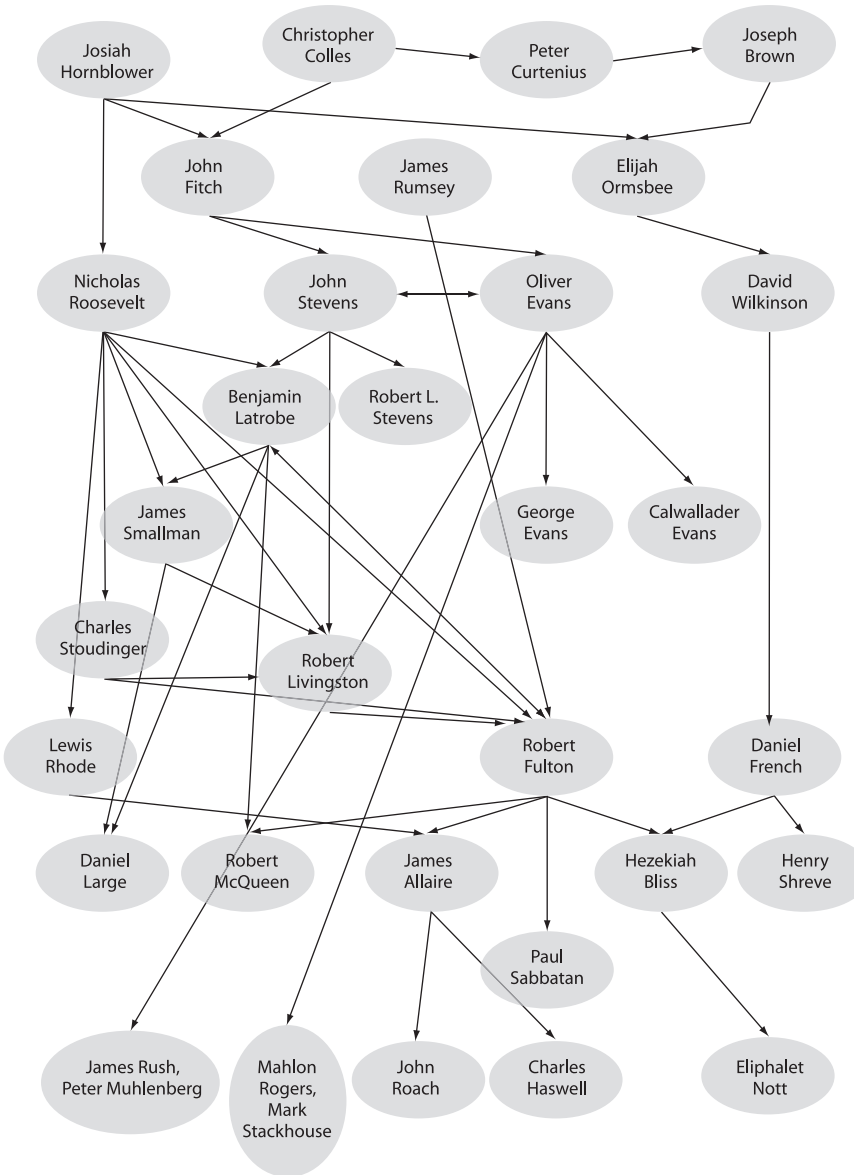

Fig. 2.2. Lineages of the steam engine. *Sources:* Carroll W. Pursell Jr., *Early Stationary Steam Engines in America* (Washington, D.C.: Smithsonian Institution Press, 1969); Brooke Hindle, *Emulation and Invention* (New York: New York Univ. Press; 1981); J. Leander Bishop, *A History of American Manufactures from 1608 to 1860*, 3 vols. (Philadelphia: E. Young, 1868). David R. Meyer, *Networked Machinists: High-Technology Industries in Antebellum America* (Baltimore: Johns Hopkins Univ. Press, 2006).

chines or the services they provided. They were innovators and as such initiated processes that would realize the potential of their products.

Even now, new products diffuse in a typically S-shaped path of the product cycle. Sales grow slowly when the product is perfected and production and marketing methods originate and then expand more rapidly as the product improves, cheapens, and broadens its uses. The engine spread in the same way. Stationary steam engines, used for manufacturing and mining, grew from Evans's 10 and a few low-pressure engines in 1812 to between 50 and 100 in 1820, perhaps 300 in 1831, and about 2,000 in 1838. Steamboat engines expanded as rapidly, and the 800 boat engines in 1838 generated 50 percent more power than stationary engines. Western boats numbered 17 in 1817, 69 in 1820, 187 in 1830, and 536 in 1840, and boats in the rest of the country had as much power.[64]

Firms' choice among hand or animal power, waterpower, low-pressure engines, and high-pressure engines depended on the cost of equipment, fuel, and labor and the benefits of reduced costs or improved quality. Inadequate production and marketing capabilities slowed early-nineteenth-century diffusion by adding to costs and reducing benefits. An 1814 letter from Fulton to a despondent Virginian brought out the problem: "There is nothing more simple for a good engineer than to construct an efficient steam flour and sawmill, or both combined, with one engine. That men should fail at Norfolk to do that which has often been done is proof of their want of experience or talent."[65] The issue, of course, was how to gain that experience.

With capabilities spread so thinly, diffusion rested on Evans, Fulton, and their collaborators. Evans claimed 28 machines in 1814 and 70 or 80 three years later. Fulton spread boats in the East then the West. Granted a monopoly of Louisiana waters, Fulton built the *New Orleans* in Pittsburgh in late 1811. Four months and 2,000 miles later, it steamed into the city for which it was named. He relied on Latrobe, Stoudinger, Roosevelt, and other eastern mechanics to construct western boats. Roosevelt piloted the *New Orleans* and maintained the engine. Four years later others completed the upstream run to Louisville, confirming the expectation that revenues would come from freight.[66]

Although Evans and Fulton made virtually none of the engines operating in 1838—both had died by 1819—their workers, suppliers, and associates were central. After making castings for Fulton, Allaire and McQueen became leading steam engine producers, Allaire having taken over Fulton's shop at his death (see fig. 2.2). Fulton influenced Paul Sabbatan and Hezekiah Bliss. Evans trained his sons George and Cadwallader, his sons-in-law James Rush and Peter Muhlenberg, and mechanics Mark Stackhouse and Mahlon Rogers. Allaire, Sabbatan, and Bliss's

Novelty Iron Works led New York City engine makers. Rush and Muhlenberg led in Philadelphia, and Stackhouse, in various partnerships, led in Pittsburgh. Each of these leaders produced stationary and boat engines. Descendants of early inventors made 9 percent of the stationary engines with known builders in 1838, led by Rush and Muhlenberg, and 21 percent of the boat engines, led by Stackhouse and Allaire.

Most producers learned of engines more circuitously. Publications provided knowledge, such as Evans's *Abortion of the Young Steam Engineer's Guide,* but they could not substitute for actual work with engines.[67] Evans demonstrated engines in his foundry and flour mills in Pittsburgh and Cincinnati and serviced engines after sale. Usage was a source of learning. David Prentice bought both Watt and Evans engines before becoming one of Louisville's biggest steam engine producers. The dispersed location of engines and steamboats diffused engine knowledge across space. Steam engineering networks spread knowledge, such as when Latrobe referred Jacob Perkins to Prentice for a comparison of the low- and high-pressure engines. Perkins then became a leading advocate of the Evans engine in Britain.

Networks also spread the dominant organizational form of the engine-making machine shop. Design and production capabilities limited entry, strengthening incentives for the skilled. Engine makers sold a wide range of machinery, such as the Troy firm that in 1830 advertised its range of offerings: "steam-engines and boilers, paper-mill screws, and various other screws, cotton factory gearing, house-boat machinery, etc."[68] Firms sold to custom order and provided ongoing personal contact. Users could better assess the reputation of nearby producers, an important factor given frequent defects of engines costing several thousand dollars. Skilled workers were hard to find and to keep. Substantial worker mobility benefited hiring firms but was a disincentive to train.

Early diffusion was limited by the tiny numbers who met the formidable requirements of vertically integrated machine making. Like textile machinery, engine making grew more slowly because it developed early, when other industries trained few machinists. Skilled workers were geographically concentrated. In 1813 John Stevens noted that boats could be constructed widely, but "it would have been almost impracticable to construct the engine in any other place than New York or Philadelphia." Pittsburgh soon joined the group, but few other towns could. Even in the late 1820s, Hartford engine makers had to go to New York to find knowledgeable workers.[69] Training, mobility, and the birth of machinery firms would relax these limits over time.

Stationary engines operated in every section of the country. Prompted by an epidemic of boiler explosions, the federal government compiled statistics on

steam engine usage and production in 1838, including detailed listings for about 1,250 stationary and 800 steamboat engines. Each region used over 350 engines. With limited waterpower, cheap wood and coal, and energy-intensive material processing, the trans-Allegheny West used one-third of all stationary engines and a larger share of horsepower, far above its share of population or manufacturing (table 2.2). Boat engines were also located disproportionately in the West. Three-fifths of the stationary engines located in towns and cities, 10 times the share in rural areas on a per capita basis. In the East and West over three-quarters were in urban areas, with a larger share of horsepower. By contrast, 86 percent of southern engines were rural, being used in sawmills, rice mills, and sugar refining.[70]

Engines found many applications. In 1814 Evans engines milled flour, sawed lumber, ran textile mills, built steam engines, rolled and slit iron, ground lead, and made wire, shovels, and paper. In 1838 lumber, machinery, textiles, and flour used half of all stationary engines; the next eight sectors added another 30 percent. Textile mills used 9 percent of engines and 15 percent of horsepower but would have used more if engines delivered the regularity of motion required by finer textiles. Machine shops, wood-turning shops, and printing also needed precise applications of power, which engines could not yet provide.[71]

Engine demand was met by the multiplication and geographical spread of engine makers. The 1838 report lists 273 U.S. engine makers; 243 of them made stationary engines and 81 boat engines (table 2.3). Some also made locomotives. U.S. firms made 98 percent of the engines, averaging six machines in use in 1838. Close to half of these firms produced a single boat or stationary engine, and two-thirds made no more than three. One-seventh of them built 10 or more machines, totaling two-thirds of all engines, and 21 firms with at least 20 engines made over half of all stationary engines and two-thirds of boat engines. Many firms, including the 21 largest, made boat and stationary engines. Firms making boat engines were fewer and averaged more engines.

Engines were overwhelmingly capital goods. Only 9 percent of stationary engines were used by the producer, nine-tenths of which were steam engine manufacturers, iron founders, and machine shops. The rest included skilled producers of instruments and hardware, along with Oliver Evans's son, who replaced his father's machine in their Pittsburgh flour mill. Self-using firms did not explain the low average output because they produced twice as many engines as other firms. Overall self-usage complemented rather than substituted for the sale of capital goods.

Engines were sold principally within regions. Four-fifths of engines were used within the region in which they were produced, typically near enough for manu-

Table 2.2. Distribution of Steam Engines by Region, 1838

	Mid-Atlantic (%)	New England (%)	South (%)	Trans-Allegheny West (%)	West (%)
All engines	30.0	17.3	19.7	33.0	12.0
Stationary engines	28.2	24.6	16.1	31.1	9.3
Boat engines	32.8	5.9	25.2	36.1	16.1

Source: U.S. Treasury Department, "Steam-Engine," 25th Cong., 3rd sess. (serial no. 345), H. Doc. 21, 1839.

Note: The trans-Allegheny West includes western New York, western Pennsylvania, and western Virginia. If the West excludes these areas, as in the last column, the Mid-Atlantic States would rise to 45 percent of all engines and the South to 25 percent. The data include only individually listed engines. The report mentions other stationary engines, including 175 in Louisiana, 40 in Alabama, 60 in New York City, and 244 in various western and southern states. If these engines were included, the southern and western shares would rise. Locomotives were also listed but are not included here.

facturers to provide service. Textile machinery firms also located near users, but because engine usage was widespread, so were engine producers. The South was an exception; reflecting its mechanical backwardness, it built only 23 percent of the stationary engines it used and only 3 percent of its boat engines.[72]

Engine making concentrated in eight large cities, including 33 of the 39 firms making 10 or more engines. Baltimore, New York, and Philadelphia were important for marine and stationary engines. Boston and Providence made stationary engines. Cincinnati, Louisville, and Pittsburgh made 95 percent of steamboats used on western rivers, almost as high a share of boat engines, and a substantial share of stationary engines.[73] Over half of identifiable engine firms were located in the eight cities, producing 74 percent of the country's stationary engines and 80 percent of boat engines.

Pittsburgh was a good example. In 1831, 11 engine-making firms averaged 30 workers, $19,500 in capital and machinery, and $30,000 in products, three-quarters for engines and auxiliary equipment. Firms making boat engines were 50 percent larger in capital and employment and in 1838 averaged 31 engines in use. New firms could more easily make stationary engines, including one 1831 foundry that made 20 engines by 1838. The 42 engine-making firms in 1838 gained from their common location. They had been interacting for 25 years. Transportation companies in the Ohio-Mississippi Valley bought marine engines there. Boat makers related closely to engine firms. Foundries, general-purpose machine shops, and skilled workers abounded. Aided by these factors, Pittsburgh firms made one-quarter of the country's engines in 1838.[74]

Table 2.3. Steam Engines with Identified U.S. Producers, 1838

	Total	Mid-Atlantic	New England	South	Trans-Allegheny West
All engines built	1,595	628	299	52	616
Engines built: share (%)		39.4	18.7	3.3	38.6
Firms	273	90	55	30	98
Average output	5.8	7.0	5.4	1.7	6.3
Engines built in region used (%)	79.9	96.5	84.0	15.7	95.4
Stationary engines built in region used (%)	83.8	96.5	88.0	23.4	97.9
Boat engines built in region used (%)	71.1	96.5	57.8	3.0	91.5

Source: U.S. Treasury Department, "Steam-Engine," 25th Cong., 3rd sess. (serial no. 345), H. Doc. 21. 1839.

Note: Only engines with known U.S. producers are displayed. Fifty-five stationary engines and 42 boat engines had known locations of production and use but without known manufacturers. Another 62 stationary engines and 269 boat engines did not list locations of production. Stationary engines were not detailed for New York City and Louisville and were underreported in areas of the West and South. Including them and other omitted machines and identifying their producers likely would have increased average firm output slightly.

Overall, engine making centered in firms, cities, and regions with developed design and production capabilities. Growth occurred through multiplication of firms. Large firms were prominent in 1820. Robert McQueen used capital of $200,000 and 82 men and boys to make steam engines, boilers, castings, and screws, and his New York competitor James Allaire invested $100,000 and employed 70 men and boys to make "steam engines and boilers for boats, sugar and other mills" and machine castings. Concentration declined as skills diffused. The two New York firms made under half of the city's output in 1838. In that year the country's largest 39 firms averaged 27 machines in operation, so annual output had to be small.[75] Industry growth resulted from spreading demand and engine-making capabilities but also from innovation in engine design, production, and application.

Invention expanded as engine making grew, in areas where it grew, and largely by those involved in the growth. Steam engine and steam navigation invention roughly doubled every decade, beginning with 9 surveyed patents in the years before 1805 and growing to 97 in the 1826–35 period. Paddlewheel and propeller patents grew about as fast as engine patents. Inventors averaged only 1.2 steam engineering patents without much variation by region. But the share of inventors did vary. Mid-Atlantic inventors received 56 percent of the total, well above the region's 39 percent of engines built and twice its share of population (table

2.4). New England patenting roughly equaled its engine-making and population shares; its domination of textile machinery patenting did not extend to engines. The South and West invented much less than their shares of usage.[76] Inventive capabilities concentrated in the East as engine making moved west.

Invention concentrated in cities, where engine usage, engine making, and engineering knowledge were centered. Inventors in eight engine-making cities received almost half of steam patents, led by New York and Philadelphia. Invention elsewhere raised the urban total to nearly three-fifths of all patents, 13 times its population share. Urban inventors often had occupations with technological knowledge. Machinists, still in their infancy, formed two-fifths of inventors with known occupations. Three shipbuilders, a pattern maker, an engineer, and a professor held mechanical knowledge. The broad awareness of engines and steamboats enabled many people to patent.

Network inventors are hard to identify for steam engineering because engine users were spread among many occupations but dominated few. Hence, one could hardly include all millers in engine networks even though some millers were. If networks are conservatively defined to include those who made steam engines or worked in steam transportation firms, network inventors made up almost one-third all inventors and received 39 percent of patents. The 32 inventors positioned to gain use (as principals in engine-making or engine-using firms) averaged 1.5 steam engineering patents, compared to 1.1 for others. Engine makers commonly patented. In almost 30 percent of the engine-making firms in the Steam Engine Report for whom principals could be identified, one or more of the partners (or occasionally superintendents) patented through 1846.[77] Many larger firms patented; among firms with patents 28 percent sold 10 or more machines, twice the share for nonpatenting firms. But small firms included many active inventors, who averaged more patents than large patenting firms (4.7 to 2.8). Although important, patenting was not part of engine makers' regular activities; many aimed at producing well-functioning machines more than improving them.

Inventive explorations often failed. Many followed Evans's futile effort to produce rotary power directly. Failing valve mechanisms, boiler designs, and gas, or "explosion," engines abounded. The high-pressure reciprocating engine improved incrementally in valve mechanisms and pressures. Boiler designs and explosion-preventing methods developed with only partial success. Two engine improvements were more basic. Led by steamboat innovators, boat and stationary engines with horizontal cylinders replaced the vertical engine with its overhead beam, which increased rotating speeds and simplified drive mechanisms. The concern that piston friction would wear the bottom of horizontal cylinders

Table 2.4. Steam Engine and Navigation Patents, 1790–1835

	Inventors	Inventor Share (%)	Average Patents	Repeat Inventor Share (%)	Patent Share (%)	Patents per Capita Index
All	154	—	1.19	14.3	—	—
New England	25	16.9	1.24	12.0	17.3	1.02
Mid-Atlantic	84	56.8	1.19	13.1	55.9	1.92
South	16	10.8	1.19	18.8	10.6	0.25
Trans-Allegheny West	23	15.5	1.17	17.4	15.1	—
West	12	8.1	1.25	25.0	8.4	0.96
Leading Cities	68	45.9	1.35	23.5	51.4	14.54
All Urban	82	55.4	1.32	22.0	60.3	12.92
Machinists	18	40.9	1.28	16.7	39.0	—
Science and invention	4	9.1	1.25	25.0	8.5	—
Other manufacturing	10	22.7	1.80	40.0	30.5	—
Trade and services	12	27.3	1.08	8.3	22.0	—
Network	14	31.8	1.64	35.7	39.0	—
Nonnetwork	30	68.2	1.20	13.3	61.0	—

Source: U.S. Treasury Department, "Steam-Engine," 25th Cong., 3rd sess. (serial no. 345), H. Doc. 21. 1839.

Note: Patents were surveyed by keyword, including steam engines, steam engine valves, steamboats, paddlewheels, and propellers. The leading city share refers to the eight major engine-making cities. The trans-Allegheny West is defined in table 2.2. Inventors were classified as urban if they received at least one steam engineering patent while residing in a city. Occupations were determined for 30 percent of domestic inventors.

was mitigated by the lower weight of the high-pressure engine. Evans noted how efficiency could improve by cutting off steam inflow before the full stroke, using the expansive power of steam to drive the piston. Robert L. Stevens, the son of the inventor John Stevens, used this principle on eastern boats in 1815; western steamboats used it by 1818. More costly and harder to construct, such engines were only coming into use in the 1830s. Zachariah Allen and others designed cutoff valves, but none gained much usage. The dominant design—the high-pressure, noncondensing, horizontal engine—was adequate for most purposes, and more sophisticated machines were limited by the need for accurate production and skilled users, limits arising from the development of engines prior to a broader machinery sector.[78]

Engine production improved slowly. Rush and Muhlenberg and other leaders used engine lathes from the 1820s, but they spread fitfully. Casting methods advanced, as Evans noted, by learning from experience. Boilers improved when wrought iron substituted for cast iron. Rolling mills formed boiler plates of more uniform thickness.[79] By the 1830s some producers made more accurate and reliable engines and boilers, but many lagged behind the frontier.

The steamboat, called by Louis Hunter "the first great American contribution to modern technology," changed greatly. Largely to increase cargo capacity, a distinctive western boat with a flat bottom and shallow hull evolved, mostly unpatented.[80] It was the outcome of incremental improvements by many interacting boat builders rather than the act of a great inventor. The direction was clear by the 1830s, though the change was not completed for another two decades. Steamboats in the West, unlike the East, utilized the high power-to-weight ratio of high-pressure engines to battle currents on upriver runs. In 1805 Evans advocated the high-pressure engine because "its power is five times as great in proportion to its weight and size, and the power may be augmented to a great degree and kept in reserve to ascend the most rapid currents." He made boat engines from 1812. In 1816 Henry Shreve used a high-pressure engine on the trend-setting *Washington,* and by the late 1820s over 90 percent of new western steamboats followed suit. Shreve probably introduced horizontal engine placement on the *Washington,* which simplified connections with the paddlewheel and stabilized the engine. Wider cylinders increased power. In Louisville average cylinder diameter grew from 15 inches 1821 to 21 inches in 1831. Because power varied with the square inches of the piston surface, the change doubled engine power.[81]

If the boat adjusted to the river in one process, the river adjusted to the boat in another. Governments led the way. To surmount the Louisville rapids separating Pittsburgh from New Orleans, Kentucky authorized a canal company, the U.S. Congress purchased two-fifths of the shares, and the canal opened in 1830. From 1820 through 1844 the federal government spent $2.5 million to remove obstructions and deepen channels in the Ohio-Mississippi river system. In 1824 the chief of engineers awarded a contract for a "machine boat" to remove snags. As superintendent of river improvements from 1826, Henry Shreve used a steam-powered snag boat with great success, reducing accidents and insurance rates and increasing night travel. Better boats and navigation reduced travel time and cost. Early steamboats made the New Orleans–to–Louisville run in a month, a quarter to a third the time of a keelboat. By 1830 times were halved. In 1820 freight costs from New Orleans to Louisville were about two cents per pound, well below the five cents by keelboat; by 1830 rates had fallen to a half-cent per pound. The steamboat had become the principal means to move passengers and upriver freight and was contending for downriver traffic.[82]

By the 1830s steam engine networks linked hundreds of engine makers and inventors to thousands of users. Americans had imported the engine but then gave it distinct designs and uses. Positive feedbacks carried the process forward. As usage broadened by industry and region, engine-making firms multiplied,

steam engineering knowledge spread, and invention sped diffusion. Yet the engine's effects remained limited. Steamboats were exceptional on the Great Lakes and the ocean, as was the stationary engine in industry. The expansive power of steam was recognized but little utilized. Engines did not produce the regular motion needed in high-quality textile and metalworking operations subject to rapid changes in load. The steam revolution had just begun.

Spreading the Written Word

When crafts embodying technological knowledge had formed in the colonial period the Industrial Revolution could evolve from established institutions. Printing was one such craft. Although printing markets, technology, and organization were fundamentally transformed during the late eighteenth and early nineteenth centuries, printers and press makers remained central to printing networks and invention. This revolution took an evolutionary form.

The printing trade fundamentally changed in the early Republic. Colonists imported most books and newspapers. Printers, few and unspecialized, focused on almanacs, sermons, and other pamphlets and on customers' individual needs. The 37 newspapers published in 1775 were mostly low-circulation weeklies. After independence, stimulated by low postal rates, newspapers multiplied to 360 in 1810 and to 1,400 in 1840, and annual copies grew from 25 million in 1810 to 196 million in 1840, led by New York, Philadelphia, and Boston dailies. Magazines grew in number and circulation, and book publication became an important part of the business. Large printing houses grew, frequently selling thousands of the same publication.[83]

A revolution in presses accompanied the growth of printing. Colonial printers used wooden hand presses that Gutenberg would have recognized, often made by joiners supervised by the printer. By 1800 Boston, Hartford, New York, and Philadelphia housed specialized press makers. Adam Ramage, a Scottish émigré to Philadelphia, was the most successful. Costing about $150, his wooden hand presses were relatively inexpensive, repairable by local joiners, and adequate for most purposes. He sold 1,200 machines. The carpenter Robert Hoe made presses from 1815.[84] Largely urban, like their customers, press makers produced mostly for custom order and often took on other work, including making plows for Ramage and woodworking for Hoe.

As markets grew, so did invention. Fifty-four presses were patented, accelerating from 1 through 1805 to 37 from 1826 through 1835. Network inventors dominated. Eleven of 20 inventors with known occupations were machinists, and 9

made presses. Another 4 were printers or engravers. Excellent evidence, often in the form of actual presses, demonstrates that 18 inventors secured some usage. Inventors clustered near printing. All were from the East, and almost all were urban, led by 14 from New York and 9 from Boston.

Presses became faster, more durable, and superior in product quality. Ramage and others perfected the wooden hand press. A toggle joint, which used a lever system to multiply power, replaced the screw mechanism for forcing down the impression-forming platen. Anticipated by an oil press and nail-making machinery, it developed independently in Britain and the United States in the 1810s. But the toggle broke wooden press frames. Around 1800 Earl Stanhope perfected an iron press in Britain, which printed the surface area in one pull, was easier to run, made a better impression, and was more durable than the wooden press. It soon included toggle joints, which it could use without breaking. George Clymer, a Philadelphia associate of Oliver Evans, developed the first widely used iron press. His Columbian press copied the overhead beam motion of the Newcomen steam engine, giving that little-used engine technological significance in the United States. A flurry of toggle joint presses appeared around 1820, including one that became Hoe's first successful product, and another by Samuel Rust, which substituted wrought for cast iron to reduce weight. Hoe bought rights to the Rust's Washington press in 1835.[85]

The press took two steps toward automation. The bed and platen press, invented by the Boston mechanic Daniel Treadwell, automatically spread ink and applied pressure to the platen. Treadwell sold about 50 machines by 1830. As improved by the Boston machinist Isaac Adams, it worked at four times the speed of hand presses. In 1813 Friederich Koenig, a German working in England, invented a cylinder press, which used a revolving cylinder to make the impression on 800 newspaper sheets hourly. David Napier, trained in a Scottish engineering family and by the eminent machine tool producer Henry Maudslay, improved the press. When Treadwell, seeking English markets, asked him to construct a machine in the early 1820s, Napier developed perfecting machines (which printed on two sides) working at 2,000 impressions per hour and newspaper models working at 1,500 to 3,000 impressions per hour.[86]

Press-making machinery firms diffused the inventions. Adams, Clymer, Hoe, Ramage, and Rust formed their own firms, and Treadwell sold patent rights. Hoe improved products and incorporated servicing in contracts. He literally copied the Napier; while assembling one, he made drawings and models and even put "the main castings in the sand," ostensibly to facilitate repairs.[87] Hoe soon sold exact copies of the Napier, which was not patented in the United States. Hoe's

1836 patent inventory included Rust's iron press, an inking machine bought from Harper and Brothers, and its own inventions. Tight networks of press makers, printers, and inventors in the major northeastern cities, linked to international knowledge, led the printing revolution.

Still, use often lagged behind invention. Hand presses of Clymer, Hoe, and Rust gained use in eastern newspapers. One-third as costly as iron presses, wooden presses persisted for lighter uses. The faster, more complex bed and platen and cylinder presses spread slowly. Both required machining capabilities only then coming into existence. Treadwell recognized such production limits when developing his first machine around 1821: "There was not a lathe to be procured large enough to turn the race of an iron bed or of a platen, and I was obliged to construct these as in the Ramage press, the former of stone and the latter of wood." Treadwell had to modify a lathe in order to make an iron platen before his machine was practical.[88] The movement to faster, larger-scale printing would be realized over the following decades.

Clock Making and Mass Production

Clock making had long been a center of mechanical knowledge. As mechanisms utilizing subtle configurations of gears, cams, pinions, and springs, clocks embodied universal principles of the regulation of motion. As devices to measure time, leading scientists and mathematicians took interest. Clock making used widely applicable metal-shaping mechanisms but was among the first sectors to develop industry-specific machines. Organized as an artisan trade, it coupled the universal features of its technology with craft modes of training and mobility. In colonial America artisans made mostly brass tower and standing clocks for custom sale.[89]

U.S. clock-making innovation targeted consumption more than science, replacing brass with wood, forming new types of clocks, and greatly extending markets. Mass production was integral to this development. In its twentieth-century usage mass production referred to large-scale fabrication of interchangeable-parts products via dedicated machinery. Such production was only coming into being before the Civil War, but its several components had wider usage. Mass production involved, first, production on a large scale for the market, not for custom order. Second, special-purpose machinery replaced hand labor. Third, production was standardized; the product and each part met designated tolerances. Interchangeable parts were assembled without modification. Textiles met the first two criteria. Shoes were produced to standard sizes, but their parts were hardly standardized. Clock making advanced in each of these dimensions.[90]

The fundamental clock innovation came from small-town producers in one area of Connecticut, led by Eli Terry, whose story is legendary. Soon after 1800 Terry sought to make clocks for the market. Around 1806 he took out contracts for 4,000 wooden clock movements (leaving the cases for others), took a year to equip a factory, met his deadlines, and retired in relative wealth in 1810. Too restless to stay retired, he designed a shelf clock (as opposed to standing and wall clocks), equipped a factory to mass-produce it, and sold tens of thousands at a fraction of the price of standing clocks. Terry is rightly interpreted to have led a revolution.[91]

Like all revolutionaries, Terry made good use of contacts with others. Two clockmakers trained him to make clocks from brass and wood and to make parts uniform enough to work in different clocks. He used this knowledge to apply brass clock design to wooden clock movements. His training provided working knowledge of gears and pendulums. In Connecticut, a center of wooden clock making, Terry learned about wooden parts and equipment to make them. Other clockmakers also turned to mass production, stimulated, like Terry, by confident distributors.[92]

Wooden clocks faced relatively few barriers to mass production. Clock parts were typically symmetrical to an axis and, unlike gunstocks, could be turned on existing lathes. Accuracy requirements were lower than in brass clocks. After patenting an expensive, little-used equation clock, Terry discovered what his son later called "the secret in money making at that time," to concentrate on the "less costly article." To mass-produce movements, Terry trained workers and built and in some cases designed machinery, including circular saws instead of traditional dividing engines to make wheel teeth. His clocks were not necessarily accurate—in 1808 Terry published a broadside that described how to adjust them if they were too fast or slow—but they were functional.[93]

Terry's success led to interchangeable-parts clock making. New products, accuracy standards, and machinery contributed to this outcome. By 1814 Terry designed a 30-hour shelf clock with movements that could be mass-produced and easily assembled and adjusted, for which he received several patents. By the early 1820s he introduced a series of gauges and jigs to guide and monitor work. By firearms' standards they were simple and inaccurate devices, but they were enough to make clocks and assess the work of contractors. Terry's mass production machinery included lathes that formed stacks of gears, though much hand work persisted. His task was eased by the simplicity of parts, modest precision requirements, and the practice of adjusting parts after assembly. These methods so lowered price that the shelf clock came to dominate the market and spread to

a far wider range of households than had traditional clocks. Emulation spread Terry's techniques. Two workers, Seth Thomas and Silas Hoadley, bought his first mill, and both men became important producers. In the 1820s Terry licensed his clock patents, and workers transmitted core technology. By the 1820s 22 firms, concentrated mostly around Bristol and Plymouth, made Terry-type clocks. They used the region's skilled workers, parts producers, and input suppliers. Foremen at different plants compared notes. Although the system was organized around contractors, parts were interchangeable. Patents grew; 56 percent of all patents through 1835 were issued over the previous decade. They clustered in New England and the Mid-Atlantic, with 33 of 35 surveyed patentees, led by Connecticut's 10. Of 13 with known occupations, 10 were clockmakers and engravers. One-third took out multiple clock patents, a share rising to one-half for those with usage. Many perfected traditional brass clocks, but Connecticut inventors concentrated on mass production, mostly in wood but with some returning to brass clocks.[94]

Connecticut innovators did not advance the centuries-long effort to measure time accurately, called by David Landes a "revolution in time."[95] But they did bring that revolution to the masses, selling cheap, relatively uniform products made on a large scale partially by machinery. Clockmakers organized a tightly integrated path to mass-produce a distinctive product. By shifting to wood, they were one of many occupations mechanizing an omnipresent material.

Transforming a Universal Input

Wood was universally important in the preindustrial economy. It was the principal building material for housing, furniture, waterwheels, and much else. One could not travel by wagon or ship without it. It was the chief fuel. Potash and bark provided indispensable chemicals. Woodworkers were central to manufacturing. In 1790 they made up 30 percent of Wilmington's manufacturing workers. In 1850 the first national census detailing occupations listed woodworkers as one-fifth of male workers other than farmers and laborers. Woodworking was especially vital to the United States, where per capita lumber consumption in 1820 was five times that of Britain.[96]

For all its variety much of woodworking followed a trajectory of mechanization. Machines to saw, turn, plane, mortise, and undertake many specialized operations had been invented by 1835. The path of woodworking innovation was much more diverse than those in textiles, printing, or clocks because woodworking was organized into many trades. Carpenters, joiners, coopers, turners, cabinetmakers, shipwrights, sawyers, wheelwrights, and carriage makers learned their

techniques on the job. Their implements varied accordingly, from reciprocating saws and pole lathes to the numberless tools to cut, drill, plane, and measure. Because woodworking was widely dispersed, innovation in this realm would not be expected to be as spatially localized as that in clocks or textiles. Millwrights and other woodworkers held some design skills, constructed wooden parts for machines, and could invent themselves. Networks transmitted knowledge, but because there were many woodworking networks spread over space, innovation varied accordingly.

Much inventive effort focused on sawmills. In a timber-rich economy colonists developed sawmills quickly following settlement. Willing to gain speed by using wide saws (wasting as much as three-eighths of an inch of wood per cut), the sawmill was a natural choice, while it was hardly used in Britain. Invention grew after independence. In a sample of woodworking patents annual sawmill and sawing patents grew from 0.5 prior to 1806 to 9 in the 1826–35 decade. Before 1816 sawing patents tripled those for planing, turning, and mortising combined. Sawmills were widely dispersed, though regional markets and, beginning with Maine, lumber-exporting areas arose. Invention also spread widely; inventors in the three northern New England states had one-tenth of patents, and southern and western inventors had one-fifth. Invention was largely rural; urban inventors had only one-fifth of patents. We know little about how inventions diffused, but millwrights and sawyers played a substantial role. Philadelphia firms supplied the growing market for saws, supplemented by heavy British imports. Some innovations improved speed and material handling. The circular saw, developed in the 1810s, began to gain use in the 1830s, stimulated by surging invention after 1825. Its capacity for rapid, continuous cutting was impeded by design problems and primitive production methods that led to vibration at high speeds. Some machinists developed more accurate equipment or entered the production of circular saws, including the printing press leader R. Hoe and Company, which made saws from 1828. But the bulk of the 3,200 sawmills in 1840 used waterpower to drive heavy reciprocating saws, much like their predecessors.[97]

Planing created a smoother finish in flooring, furniture, and wagons. Hand planes had been adapted to many functions; one New York carpentry shop contained 38 types. Planing machine patents rose after 1825, led by carpenters, other woodworkers, and machinists. Urban inventors received over half, nearly three times the share for sawmills, partly because planing mills located near markets for finished wood. Two notable inventions were vastly superior to handwork. In 1828 William Woodworth invented a planing machine that cut tongues and grooves; reportedly, its output in 15 minutes equaled a skilled worker's output in

a day. Invented by a carpenter and perfected at considerable cost, it diffused by the sale of patent rights assigned on a geographic basis; the Philadelphia county rights cost $6,000. The second, patented by Thomas Daniels in 1834, would find extensive usage in heavier work.[98]

Hand lathes turned a great variety of products with curved shapes. The Census of 1820 demonstrates the breadth of lathe users. They included 26 furniture makers, 3 clockmakers, 5 button makers, 17 spinning wheel firms, 2 agricultural implement producers, 8 carriage and wagon establishments, and others making castings, machinery, and marble. Woodworking lathes were inexpensive; furniture makers using them averaged $1,200 in capital and five employees.[99] Lathe invention accelerated with usage. New lathes greatly increased turning speeds in making chairs, rake and hoe handles, and wheels. The most original invention was the pattern lathe, patented by Thomas Blanchard in 1820 to turn gunstocks. Lathes typically turned objects concentric to an axis and could be adapted to make oval parts. Blanchard's lathe differed fundamentally; it copied three-dimensional irregular shapes by having a cutter follow a pattern. The pattern lathe dramatically reduced labor costs to make firearms, shoe lasts, implement handles, spokes, hat blocks, and oars. It diffused largely through patent licensing and assignment, but Blanchard used it as a firearms contractor and sold it in machinery firms, and New England mechanics covertly spread it. By the mid-1830s it was used to make firearms at the national and private armories, virtually all lasts, and had begun to spread to other uses.[100]

In houses and furniture mortising and tenoning joined wood pieces by fitting protrusions (tenons) into holes (mortises). Mortising and tenoning patents were few before 1826, but 38 were issued over the next decade. Among the most important were George Page's 6 patents. He and others made and sold the machine. The McLane Report credits Josiah Fay with selling 50 patented tenoning machines in 1831 at an average price of $50. Just beginning to penetrate wood-joining applications in the 1830s, such machines would challenge hand methods.[101] Metalworking innovation generated two other central wood-joining devices, nails and screws. Machines made nails since the 1810s and screws from around 1830. For much joining work the dominant material of the machine age was supplanting joining techniques of the wooden age, and metalworkers were the key inventors.

By 1835 mechanization began to challenge the craft character of cutting, planing, turning, and joining wood. Innovation came incrementally from below, with little support from abroad or above. Perhaps because of the incremental character, no Evans or Slater or Terry stands out as a revolutionary innovator.[102] Woodworkers were central agents, supplemented by machinists. Innovation was

spatially broad, with much rural and small-town invention in most sectors. It was also differentiated, located in different areas and responding to distinct technological problems and markets. Yet convergences linked machines working at speeds of thousands of feet per minute.

This innovational path faced limits. The contemporary woodworking machinist John Richards identified several. Carpenters had little training in designing machines that worked rapidly and accurately, which led to dysfunctional designs. What Richards called carpenters' "architectural ideas" led to machines designed in "all conceivable forms except those that the strains would indicate; figures of vines and shrubbery, 'pomegranates and lily-work' were raised in relief." Distant from metalwork, woodworkers relied too much on wooden parts. The dispersion of woodworking machinery production limited the spread of useful knowledge, as did secrecy among woodworkers. Patent licensing helped spread knowledge, though licensees had difficulty building adequate machinery. The small scale of production units was also a limiting factor.[103] By the 1830s the growth of regional markets and the emergence of woodworking machinists and woodworking machinery firms were overcoming these limits, with profound implications for the future.

Firearms and Government-Led Innovation

Some mechanization processes involve such basic transformations that economic agents, acting on their own, cannot accomplish them at all, or at least not at anything like the observed pace. In these cases other institutions are needed to innovate. Firearms was one such case, and the government played a vital role. Tariffs and patent protection affected private activity in many industries, but they did not directly determine how firms produced and learned. In firearms the government ran public armories, financed private armories, defined the production process, and organized and regulated technological learning. As a result, large firms, long production runs, and movements toward interchangeable-parts metalworking characterized the industry.

A craft of gunsmiths flourished in the colonial period, but it had little prospect to generate factories. Factory production involved discontinuities in scale, investment, and production. The Census of 1820 documented the break with past practice; six firms built armories that averaged $49,000 in capital, 55 workers, and $28,000 in product—each from 20 to 30 times that of gunsmiths. Sales were a different order to magnitude; gunsmiths produced a few guns at a time, not the thousands in government orders. Factory investment was far greater; the 79

gunsmiths recorded in the Census of 1820 averaged $1,700 in capital.[104] Factories differed in technology and organization. Gunsmiths had skills in metalworking, woodworking, and the design of mechanisms made of moving parts, but they had no knowledge of mass production. Innovations to mechanize production of thousands of firearms were much greater than those required to mass-produce clocks. Because metalworking and woodworking machinery was little developed, the burden of innovation fell largely on firearms producers.

The federal government led in overcoming each discontinuity. It formed markets. The six large firms in 1820 all had government contracts. The practice began with Eli Whitney's 1798 contract for 10,000 firearms and continued through the 1830s. The government supplied capital to private firms through substantial advances from contracts, including all but $2,400 on Whitney's $134,000 contract and $80,000 for Simeon North's 1813 contract.[105] Large orders, capital advances, and high enough prices made mass production possible. Achieving it was another matter; some early plants were handicraft units writ large. In its most complex role the government transformed production by defining the product, organizing the process, and structuring technological learning. It established quality standards, inspection systems, and an operational principle of having uniform firearms. It also formed public armories at Springfield, Massachusetts, in 1794 and at Harpers Ferry, Virginia, in 1798 and established a system of cooperation in which technical advances were shared among armories and contractors.

Because of the government's central role, firearms developed in a planned process quite unlike the private, market-mediated processes developing other technologies. By the time its 1813 pistol contract with Simeon North stipulated that "any limb or part of one pistol may be fitted to any other pistol," the government's purpose had become clear: to secure firearms that were easily repairable because parts were interchangeable. Uniformity was desired even if it meant higher prices. Jefferson was the initial advocate, when, as minister to France, he observed and endorsed French efforts to build interchangeable-parts firearms, noting that "the advantages of this, when arms need repair, are evident." The French system, championed by the inspector general of the French artillery, found advocates in the U.S. War Department, particularly in the Corps of Artillerists and Engineers formed in 1795. Private forces added momentum. At first Eli Whitney argued for his firearms contract based on lower costs, but he soon became a chief advocate for uniformity. The difficulties of repairing firearms in the War of 1812 added to the impetus. When authority over arms contracts and public armories was placed in the Ordnance Department, the goal of interchangeable-parts production had become institutionalized.[106]

The goal was pursued through several policies. Contracts to private firms and directives to public armories stipulated that arms conform to a designated standard. Government-supplied pattern weapons set standards, which were enforced by an inspection system—initially done by eye and later by gauge. Continued contracts depended on a firm's ability at least to approach uniformity. The government advocated mechanization and spread knowledge of methods. Public armories were centers of inspection and technological communication as well as production.[107]

Private contractors initially led in realizing the goal. The federal government let contracts with 27 private firms and individuals in 1798 and 1799 and another 18 in 1808, varying from 25 to 10,000 firearms and auxiliary parts. Many failed, including the Pennsylvania gunsmith William Henry Jr., who received a contract for 10,000 muskets in 1808. Government inspectors rejected his first shipment and barred him from further orders.[108] Others were successful. The leading innovator, Simeon North of Middletown, Connecticut, pursued uniformity through specialized workers, jigs and fixtures to hold the work and guide the tools, and gauges to ensure conformity with a model firearm. Initially, he reorganized gunsmith's hand forging and filing, but repetition provided scope for mechanization. Water-driven trip hammers, which had forged agricultural implements from 1800, welded gun barrels. North initially made scythes, so presumably he knew the technique. Around 1816 he invented the milling machine, a basic machine tool that chipped metal with a rotating steel cutter carrying a series of cutting tools on its circumference. Private contractors developed die-forging techniques and machine tools to bore, drill, and turn. By 1816 North's firearms were lauded for their uniformity, at least by the loose standards of the time.[109] Such innovations anticipated uniform production but hardly achieved it.[110]

Public armories originally used craft methods and modest divisions of labor. From 1815 Roswell Lee vaulted the Springfield Armory into national leadership. Lee worked closely with the visionary heads of the Ordnance Department, whose chief, Colonel Decius Wadsworth, learned the benefits of uniformity in the Corps of Artillerists and Engineers. Wadsworth and his assistant and successor, George Bomford, asked Lee to prepare standard muskets and inspection gauges to be used at all armories. Lee had gauges made to inspect finished products and parts under construction, together with master gauges to check those used in production. Organizing Springfield's production to meet the standards proved challenging. Lee further divided labor, extending the 34 distinct positions in 1815 to 100 in 1825. Armory workers developed some machines, including Sylvester Nash's barrel-turning lathe. Lee introduced North's milling machines and barrel-

forging and turning techniques. In trying to perfect his barrel-turning lathe, Asa Waters consulted Thomas Blanchard about turning the asymmetrical end of the barrel, and Blanchard's cam solution led to contracts at the national armories. Blanchard soon developed his pattern lathe and used it as an inside contractor at Springfield, employing armory machinery and power to make gunstocks at a fixed price. Recognizing that his lathe was part of a system, he developed 14 self-acting woodworking machines that substantially sped up the process.[111]

Whereas the Springfield Armory was in close contact with innovative contractors, the Harpers Ferry Armory depended more on Philadelphia-area gunsmiths, which inhibited change. Harpers Ferry developed the division of labor slowly and did not purchase Blanchard gunstocking equipment until Lee temporarily superintended it in 1827. The major exception was the rifle works, formed in 1819, when the government contracted with Maine woodworker John Hall to build his patented breechloading rifle. Hall promised fully interchangeable firearms and succeeded by 1824. He developed a system of special-purpose milling and drop-forging machinery, 63 gauges, and the key principle of locating the fixtures in relation to the same point on the part so that errors elsewhere on the part did not become reference points for later work. The standard of interchangeability was still loose; as one expert noted, "The joint of the breech-block was so fitted that a sheet of paper would slide loosely in the joint, but two sheets would stick." Hall's system was a remarkable accomplishment, a result achieved by employing as many men to design and make machines as he employed making firearms.[112]

The government organized a communications system through which units learned from each other. The federal armories became the system's centers, especially the Springfield Armory. Inspection by Springfield Armory personnel, though a source of disagreement, did enforce standards, and it became more cooperative when armory staff worked with contractors to minimize rejects. Springfield was a center of technology sharing. It loaned out tools, patterns, and skilled pattern makers and toolmakers, and performed services such as rolling iron. It shared knowledge of machine design, manufacturing techniques, gauging, and inspection methods. It learned from private firms, and firms learned from each other. Knowledge sharing was entailed by the contract system, which required contractors to open their shops to the armory and other contractors. The Ordnance Department made clear that future contracts depended on technological progress and knowledge sharing. The Armory also secured agreement from contractors not to employ each other's workers without recommendations from previous employers. Sharing overcame potential market failures; as Michael

Best put it, "The Armory provided three services undersupplied by the market: information, labor education, and technology transfer."[113]

Technology sharing was strongest around the Connecticut River Valley, where Armory and firm personnel toured plants, shared equipment and knowledge, and moved among establishments. Sharing was less common elsewhere, though the national armories cooperated to achieve uniformity between them. Harpers Ferry benefited from a regular flow of New England patterns, gauges, and personnel such as Sylvester Nash and Thomas Blanchard. The reverse flow was limited, except from Hall's Rifle Works. After superintending Harpers Ferry, Lee brought Hall's innovations to Springfield. When North got a contract to make Hall's breechloaders, Hall transferred pattern arms, gauges, and knowledge, and North succeeded in producing rifles that interchanged with Hall's. In addition, Nathaniel French left the Rifle Works for North's plant and the Springfield Armory.[114]

Patenting integrated uneasily into this system. Most firearms patents before 1836 improved muskets, rifles, and pistols. A percussion ignition system that Joshua Shaw patented in 1822 was especially important. Many tested the inventions, but except for Hall's breechloader and his percussion carbine of 1833, the Ordnance Department accepted few new weapons until the 1840s. State militias tried others, such as Isaiah Jennings's repeating rifle. Some patented production methods, including a number of barrel lathes, Blanchard's pattern lathe, and Hall's metal-cutting equipment. Whereas new firearm designs were dispersed, over half of the manufacturing patents were located at or immediately around the national armories. Many manufacturing inventions were not patented, including North's milling machine, Blanchard's other stocking machines, and some of Hall's equipment; contractors who were obliged to share knowledge freely had less reason to patent. Hall must have recognized this was the case when he noted that North used his equipment without remuneration; Hall's return came from his own contracts.[115]

The government structured a largely self-contained dynamic. Although grounded in the gunsmith craft, the key innovations took place in the Ordnance Office, national armories, government contractors, and their suppliers. The government subsidized the development of uniformity by providing capital, markets, and knowledge. It chose a more expensive technique over cheaper gunsmithing methods, recognizing that its subsidy of Hall was an experiment in uniformity. The experiment paid off; even though Hall's breechloader lost its appeal, his methods of interchangeability spread to other government contractors.[116] The system structured market interactions, but it did not supplant them. Although the milling machine and die-forging methods were products of the armory system, purchase of equipment and patent rights was common; Springfield

benefited from purchasing David Wilkinson's lathe castings and using his lathe, complete with slide rest, as the basis for its barrel-turning equipment.

The accomplishments of the armory system by the 1830s should not be overestimated. In 1839 the Springfield Armory employed six workers for each machine. One innovative armory used a single milling machine. Interchangeability was an infrequently accomplished goal, and the absence of interchangeability directed invention, such as a Blanchard machine to adapt his stocks to lock plates of varying dimensions. One reason for such limits was the difficulty of making precise machinery when the industrial lathe was just spreading and the metal-planer was not yet in use.[117] But the impetus toward greater uniformity and mechanization was clear, and the trajectory would continue through the Civil War, even as the armory system was basically changed.

Varieties of Mechanization Paths

After visiting the United States in 1831, Alexis de Tocqueville remarked that "no people in the world have made such rapid progress in trade and manufactures as the Americans."[118] By then, about the time the British Industrial Revolution had been completed, the United States had internalized much of the new technology in textiles, engines, and printing and in each case had developed its own improvements. Americans also began to mechanize clocks, woodworking, and firearms, industries firmly within the craft domain in Europe. The once-backward United States was catching up in some sectors and taking the lead in others.

The breadth of mechanization was all the more remarkable because it occurred along largely separate paths, differentiated by core technologies and knowledge-transmitting institutions. Paths differed in the interactions that structured pioneering activities. The knowledge of spinners, gunsmiths, clockmakers, carpenters, or printers was held within the craft but not by other crafts, so that innovations emerged out of separate groups. The pioneering effort often concentrated in a single firm and location and spread from there. Diffusion broadened the group aware of the technique but did so among practitioners, those firms and occupations in communications networks using and making the new technique. Practitioners developed the technique, and new knowledge spread within networks, which formed an entry barrier to the uninitiated. Limited access to skilled labor reinforced the barrier. Facing different markets, production conditions, and limits, innovators focused their efforts mostly on their own industry.

Evidence for such autonomy is abundant. Because paths evolved in different networks, participants in each path intersected little with those in others. Textile

principals and machinists, printers, clockmakers, and gunsmiths learned and invented within their industries. Moreover, industries differed spatially, and invention localized accordingly. Mass production textiles concentrated around Rhode Island and eastern Massachusetts, large-scale clock making in part of Connecticut, mass production firearms in the Connecticut Valley, and printing in large cities. Geographic diffusion often rested on the movement of practitioners, so that new and old methods coexisted in different regions, in cases leading production to concentrate near new techniques.

These paths were hardly impermeable. In cases such as Wilkinson's or Blanchard's lathe, innovations in one sector were used in others. Such linkages were important but not critical, at least until the 1830s. Wilkinson's lathe spread slowly in firearms; Hall's machinery depended little on it. Blanchard's spread selectively outside firearms. Although sawmills, textile mills, and printing offices used steam engines by the 1830s, each developed independently of engines based on other power sources. Some people were involved in many paths—Blanchard's lathe, wool-shearing, nailmaking, and steamboat inventions linked him to several—and learning in one type of invention could have informed others. But as in Blanchard's case, spillovers from one invention to another were not large, and most inventors patented in a single industry.

Understanding innovation paths is complicated by their variety. Each path involved pioneering, diffusion, machine production, usage, and ongoing invention, but these activities occurred in varied ways. Table 2.5 outlines the contrast. Paths originated differently. Textiles and printing presses developed largely or significantly from abroad, and technologies were international throughout the period. Engines and firearms involved such diffusion, but later development was largely internal, either because the United States developed in different directions (e.g., engines) or because development ceased in the originating countries (e.g., firearms). Woodworking and clock making developed from below, led by American craftsmen. Pioneering in firearms was the most distinctive because of the government's role in contracting, production, and product definition; innovation from above stamped the path.

Innovations spread in various ways. The biggest general contrast was between diffusion through capital goods sales (such as in textiles, steam engines, and printing presses), producer mobility or patent licensing (e.g., clock making and woodworking), or cooperation (e.g., firearms). Capital goods sped diffusion and overcame barriers to knowledge acquisition. They were less important when craft producers held extensive knowledge. Woodworking and clock making were more self-contained in that producers also made machines used in their production

Table 2.5. Innovation Paths, 1790–1835

	Cotton Textiles	Steam Engines	Printing Presses	Clocks	Woodworking	Firearms
Pioneering						
Mode	Diffusion	Diffusion & invention	Diffusion & invention	Invention	Invention	Invention
Initial innovation	Water frame	High-pressuree engine	Iron press	Mass prod. Wood clock	Sawmills; planers; lathes, mortising	Mass prod. Jigs and gauges
Pioneer	Textile machinist	Technologically skilled	Pressmakers	Clockmakers	Woodworkers	Gunsmiths
Unit	Partnership & corporation	Partnership	Partnership	Partnership	Partnership	Government & contractors
Diffusion						
Mode	Machinists, machinery firms, patent licenses	Engine firms	Press firms	Clockmakers	Woodworkers Patent licensing	Government; machinists
Leading location	R.I., Mass., N.Y., Pa.	Dispersed cities	Three eastern cities	Eastern Conn.	Dispersed	Conn. River
Extent	Wide; international	Moderate; late	Wide; international	Wide in Conn.	Late; modest	Wide
Knowledge spread	Worker mobility	Worker mobility	Worker mobility	Worker mobility	Worker mobility	Sharing; mobility
Machine production						
Constructor	Textile machinist	Engine maker	Pressmaker	Clockmakers	Woodworkers	Armories
Organization	Machinery firm increasingly	Machinery firm	Machinery firm	Clockmakers	Self-used, some purchases	Mostly self-used
Dominant methods	Iron; lathes, drills	Iron; lathes, boring	Iron; lathes, toggles	Wood; saws, Indexes, gauges	Wood; planers, saws	Metal milling & lathes; wood
Usage of innovation						
Discontinuity	Great	Modest	Modest; growing	Great	Modest mostly	Great
Scale of users	Large	Moderate	Moderate; growing	Moderate/large	Small	Large
Users, number	Hundreds	Thousands	Hundreds	Tens	Thousands	Ten
Users' market	Consumer	Various	Consumer	Consumer	Various	Government
Market scale	Mass	Mass, custom	Small to mass	Mass	Mostly mass	Mass
Scope	One industry	Universal	One industry	One industry	Many industries	One industry
Government role	Patents; tariffs	Patents; monopolies	Patents; tariffs	Patents	Patents	Organization; sale
Ongoing invention	Textile machinists	Engine makers and users	Pressmakers and printers	Clockmakers	Woodworkers	Armorers

Table 2.6. Internal Patenting by Innovation Path, 1790–1835

	Textiles	Steam Engines	Printing Press	Clocks	Wood-working	Firearms
Inventors	298	154	32	36	221	52
Average patents	1.31	1.19	1.28	1.39	1.10	1.06
Repeat inventor share (%)	16.4	14.3	25.0	22.2	9.0	5.8
1826–35 share (%)	44.1	52.7	68.3	56.0	67.6	54.5
Location						
New England (%)	47.6	16.9	40.6	50.0	34.1	29.4
Mid-Atlantic (%)	41.7	64.2	59.4	44.4	50.0	45.1
South (%)	4.8	10.8	0	5.6	9.1	13.7
West (%)	5.9	8.1	0	0	6.8	11.8
Urban (%)	20.7	50.0	78.1	33.3	16.8	15.7
Occupation						
With known occupations	52	44	21	12	10	10
Machinists (%)	59.6	40.9	52.4	8.3	40.0	20.0
Science and invention (%)	1.9	9.1	0	0	10.0	10.0
Other manufacturing (%)	19.2	22.7	42.9	83.3	30.0	50.0
Trade and services (%)	19.2	27.3	4.8	8.3	20.0	20.0
Network (%)	62.0	31.8	76.2	66.7	50.0	20.0

Sources: Edmund Burke, *List of Patents for Inventions and Designs, Issued by the United States, from 1790 to 1847* (Washington, D.C.: J. & G. S. Gideon, 1847); U.S. Patent Office, *Subject Matter Index of Patents for Inventions Issued by the United States Patent Office from 1790 to 1873, Inclusive* (Washington, D.C.: Government Printing Office, 1874); various city directories.

processes. Firearms manufacturing was distinctive because the government led and organized the spread of innovations. In each case the mobility of trained workers to other firms or new firms spread the technique.

Machine production differed in terms of materials, agents, and methods. Machinists came to use iron-casting, forging, and cutting methods to make textile machines, steam engines, and printing presses. Heavy machines such as marine engines and power looms required a size and material-manipulating capability that light machines did not. Interchangeable-parts production in firearms and clock making went well beyond functional standardization, which included pieces of cloth or newspapers. The goal of uniformity led to precision measurement; the use of fixtures, jigs, and gauges; and special-purpose machinery. These methods, characteristic of what has been called the "American system," had little existence in other sectors by 1835. Yet other sectors also tried to gain economies of scale by using designs and patterns for batches of products.

The form of usage varied among paths. The discontinuity from craft produc-

tion was greatest in factories, where scale and capital investment were largest and major organizational changes were needed. Merchant wealth, corporations, or government funding proved important in such settings. Elsewhere production scale and technology were less discontinuous, and usage involved fewer changes. The extent of usage affected the organization of machinery production; capital goods firms formed most readily when users were numerous and the technologies of machine making and machine usage differed.

Usage differed greatly in extent. Many sectors used steam engines and woodworking machines so that their communications networks were wider. They were general-purpose technologies; learning for one purpose spun off to others, as stationary engines did for boats or as the gunstocking lathe did for last making.[119] The two technologies differed in that engines, like waterwheels, provided only power, whereas wood was used as a material, an instrument of production, and a fuel. Other technologies were used primarily within a single industry. The thousands of users of engines or woodworking machines did not lead to the creation of large machinery firms; engine-making firms remained small, and few specialized woodworking machine firms existed. Local or regional custom markets led to the multiplication of machine-making units.

Each path generated ongoing invention but in different ways. Inventors varied in their persistence. Although professional inventors did not characterize any path, one-quarter of printing press inventors received more than one patent in the field (called an "internal patent"), whereas the share receiving more than one internal patent declined to 6 percent in firearms (table 2.6). On all paths continuing invention was highest for those who gained usage, either as capital goods, led by printing presses, or in mass production, led by clocks.

The location of inventors varied with the location of practitioners. New England led in clocks and textiles and the Middle States in engines, woodworking, and presses. The South and West together had 20 percent of patents only in firearms; their 19 percent of sawmill patents, twice as high as their share of other woodworking patents, reflected their strength in wood extraction. Similarly, the share of urban inventors varied from 16 percent for firearms and woodworking to 78 percent for printing presses. Along each path invention was undertaken by technologically skilled practitioners far out of proportion to their numbers in the population. Machinists were especially significant in textiles, engines, and presses, in which capital goods spread innovations. Crafts were more important in clock and firearms invention. In all sectors network inventors were central to patenting, though these networks varied in their regional and urban or rural locations.

Finally, the timing of these paths varied significantly. Only textiles undertook meaningful mechanization before 1805. Important engine, clock, and press innovations began in the next decade, though more fundamental press improvements came later. The mechanization of firearms production began after 1815, and new machinery in woodworking came on line after 1825. Correspondingly, the share of patents in the last decade of the period was lowest in textiles, engines, and clocks and highest in woodworking and printing. Yet invention in each innovation path accelerated; each had more than two-fifths of their patents in the course of the 1826–35 decade.

A final puzzle concerns why, if paths were so varied and autonomous, they all occurred in the same period. To the extent that innovation paths were independent, their simultaneity must be explained by other factors. Several candidates suggest themselves. The size and growth of markets in an economy of rapid population growth and transportation improvement, complemented by relatively high wages and relative equality, fostered improvements in textiles, printing, clocks, and woodworking. Resource abundance affected woodworking, steamboats, and the choice of high-pressure engines. Public policies about tariffs, patents, and education affected many sectors. Cultural factors helped as well. Innovation did not face barriers of entrenched interests, at least relative to Britain and the Continent. Republicans and Federalists both supported technological change, and few organized forces opposed it. The widespread willingness to innovate extended beyond mechanization to craft products, putting-out systems, and engineering projects, and total patenting grew at the same rate as in early mechanizing sectors. Diffusion from Britain was evidently important in textiles and printing and played some role in steam engines.[120] Common access to millwrights, blacksmiths, woodworkers, and other craftworkers with some technological knowledge also affected many sectors.

Yet the variety of innovation paths and the lack of technological change in many other sectors cast doubt on any overarching explanation. Given the starting point of an economy fragmented by crafts, this diversity is hardly surprising; a single dynamic of development would have required a discontinuous change that revolutionized the economy from abroad or above. Firearms and clocks followed the contours of interchangeable parts, but others did not. If there was an "American" system common to production, it must be conceived more broadly. Resource abundance fostered mechanization in woodworking, slowed the introduction of stationary steam engines, and had little direct relevance to printing presses or textiles. All mechanizing sectors benefited from increasingly large

markets for final products, but so did sectors that were not mechanizing. In any case the U.S. market was smaller and more fragmented than Britain's; even in firearms British government demand was far greater. Each path rested on capabilities from domestic crafts. Yet skills were modest by European standards, and the crafts generated little mechanization before 1790 and played different roles in later innovation. The backwardness of the United States suggests why it developed by diffusion and why U.S. techniques relied longer on woodworking and mechanically simple techniques than did Britain. Still, in some sectors development occurred by innovation.

Technological change in the early Republic thus must be understood more as a set of relatively autonomous paths responding to different factors than as an integrated American road to mechanization. Moreover, as the far greater British textile dependence on steam power indicates, the United States integrated these paths less. This is an important conclusion because it puts emphasis on the process of change itself, rather than on the external factors to which change responded. The mechanical age in the United States was born when multiple technical-institutional transformations organized networks that spread and developed new techniques and the knowledge underlying them.

Ongoing Mechanization, 1836–1865

Processes of technological change, once begun, need not continue. Changes could level off, maintaining gains but not extending them, much as the printing press retained the form Johannes Gutenberg gave it through the eighteenth century. Before the Industrial Revolution such episodic change had been the norm. In the United States as well as Britain the Industrial Revolution broke the pattern, forming an ongoing innovational dynamic at the core of modern economic development.

The momentum of early-industrializing sectors, in a context of demand growth, contributed to continuing innovation. Communication networks specific to each sector had diffused new knowledge among practitioners before 1835 and continued to do so afterward, expanding the ranks of potential inventors. But two factors may have modified network-based dynamics. First, each path faced limits in production and design capabilities that practitioners were not well positioned to overcome. Outside factors might have contributed from above, through the evolution of applied science and government policy, from abroad via diffusion, and from below, through spillovers from other innovation paths. Second, communication modes outside networks, including publications, education, and patent assignment, might have reduced the importance of practitioners' learning, enabling many more to invent. Both factors might have accelerated innovation by broadening the institutions that contributed to it. This chapter begins to address the issue by examining ongoing innovation in the six sectors that began to mechanize before 1835.

Continuing Invention

Innovation in early-industrializing sectors continued after 1835 along established paths, though growing in scope and changing in form. A study of 3,900 patents identifies the trends. Invention grew in each sector. Few patents were issued before 1806 (table 3.1). Average annual patents in the next decade surged in each of the six

Table 3.1. Patenting Trends in Early-Industrializing Sectors, 1790–1865

	Textiles	Steam Engines	Printing Press	Clocks	Wood-working	Firearms	Totals
All patents	1,270	812	267	226	474	863	3,912
Annual patents							
1791–1805	0.8	0.8	0.1	0.1	0.1	0.1	2.1
1806–15	11.7	3.4	0.6	1.1	1.0	0.8	18.6
1816–25	8.9	4.1	0.6	0.9	0.4	1.5	16.4
1826–35	17.2	9.7	2.8	2.8	7.4	3.0	42.9
1836–45	13.9	9.1	2.1	1.4	5.8	4.5	36.8
1846–55	27.2	9.6	7.4	2.0	13.2	11.5	70.9
1856–65	46.9	44.1	13.1	14.2	19.4	64.8	202.5
Patent shares							
1791–1835	30.7%	22.7%	15.4%	22.1%	19.0%	6.4%	20.7%
1836–65	69.3%	77.3%	84.6%	77.9%	81.0%	93.6%	79.3%

Sources: Edmund Burke, *List of Patents for Inventions and Designs, Issued by the United States, from 1790 to 1847* (Washington, D.C.: J. & G. S. Gideon, 1847); U.S. Patent Office, *Subject Matter Index of Patents for Inventions Issued by the United States Patent Office from 1790 to 1873, Inclusive* (Washington, D.C.: Government Printing Office, 1874).

Note: Patents were chosen based on a keyword search of major types of patents. This method does not completely sample any type; using Patent Office classifications for numbered patents would come closer to this objective. But the method adopted has the distinct virtue of forming a consistent data set over the whole period, including the pre-1836 period, for which classifications do not exist. Data for pre-1836 excludes sawing and sawmill patents.

sectors. From the 1806–15 levels annual patents quadrupled by the end of the period in textiles and grew over tenfold in every other sector. As a result, each sector received over two-thirds of its patents from 1836 through 1865.

If unused, patents did little to advance innovation, and the analytical importance of patent data might be questioned.[1] Many, perhaps most, patents failed to increase productivity or improve quality, but others were widely used. As patent assignments indicate, many patents were considered valuable enough that others purchased them. Assignments transferred ownership rights to the assignee, varying from the full right to the patent, a percentage of patent rights, or rights to certain locations or uses. Using Patent Office assignment records available from 1836, assignments through 1864 were determined for about 200 inventors with known occupations.[2] Their patents received about 1,300 assignments, led by 151 for a steam engine and carpet inventor.

About two-thirds of all surveyed inventors assigned at least one patent from 1836 through 1864 (table 3.2). Inventors assigned patents to others who might use them but also assigned them to their own firms, assigned powers of attorney, assigned patents to groups including themselves or to other family members with whom they might have worked, and even used patents as collateral for loans. Excluding

these latter types provides a conservative estimate of arm's-length purchase for the assignee's own use, called "assignment to others." Over three-fifths of inventors met this criterion for at least one patent. Some assignments were outside surveyed patent categories, such as the textile patentee who assigned steam boilers. About 42 percent of inventors assigned patents to others within the surveyed patent category, ranging from 27 percent for clock inventors to 50 percent for textile and firearms inventors. Inventors who assigned surveyed patents to others received more patents in that category, in part because assignment supported continuing invention.[3]

Assignments hardly guaranteed that patents were used. Purchasing patent rights was a gamble that often failed. Yet many assignments had substantial value. So did many patents that were not assigned. Many of the most important inventors used patents in their own firms and assigned to their own firms, if at all. Others licensed patent rights to others without assignments. A broader measure of inventors positioned to gain use includes principals of relevant machinery firms or machine-using firms (such as textile machinery or textile firms for spinning and weaving patents), patentees who assigned to their own firms, and those who assigned patents to others. From three-fifths to three-quarters of patentees had such potential usage (see table 3.2). As case studies make clear, many inventions did gain widespread use.

Important aspects of earlier innovation paths persisted, including patentees' location, extent of invention, occupations, and network linkages. Textile patenting became even more concentrated in New England, with over three-fifths of patents after 1835 (table 3.3). Most patentees remained outside cities (defined as those with over 10,000 population in 1850), though the urban share grew. New England remained the largest clock-patenting region, again mostly outside larger cities, though many more lived in smaller industrial villages and towns. Steam engine patents continued to concentrate in the Mid-Atlantic States and in cities, though the Midwest ascended. Eastern cities again dominated printing patents. Turning, planing, and mortising patents remained eastern but moved west with industry. Firearms showed the biggest change, as New England and cities ascended. Industries differed in inventive location much as they had before 1835.

Inventors had similar characteristics between periods. They averaged between 1.1 and 1.6 surveyed patents in both periods. Clearly, patenting had not yet become the preserve of specialized inventors. In both periods machinists constituted at least two-fifths of inventors in every sector except clocks and firearms (table 3.4). Other manufacturing occupations specialized in their own sectors, including textile trades, printers, clock makers, carpenters, and gunsmiths. Engineers, patents agents, and draftsmen increased from 5 to 12 percent of inventors,

Table 3.2. Patent Assignments by Type of Invention

	Textiles	Steam Engines	Printing Press	Clocks	Wood-working	Firearms	Totals
Inventors	24	23	48	26	49	32	202
Any assignments (%)	75.0	65.2	64.6	61.5	67.3	71.9	67.3
Assignment to others (%)	70.8	56.5	60.4	50.0	63.3	65.6	61.4
Internal assignments (%)	50.0	39.1	43.8	42.3	46.9	53.1	46.0
Internal assignments to others (%)	50.0	30.4	43.8	26.9	44.9	50.0	42.1
Average internal patents							
Assigned to others	4.8	2.7	3.8	2.0	3.8	5.5	4.0
No such assignments	2.4	2.7	2.5	2.4	1.9	3.3	2.5
Inventors with potential use (%)	62.5	65.2	70.8	76.9	69.4	59.4	67.8

Sources: Edmund Burke, *List of Patents for Inventions and Designs, Issued by the United States, from 1790 to 1847* (Washington, D.C.: J. & G. S. Gideon, 1847); U.S. Patent Office, *Subject Matter Index of Patents for Inventions Issued by the United States Patent Office from 1790 to 1873, Inclusive* (Washington, D.C.: Government Printing Office, 1874). Patent assignment data are from U.S. Patent Office, "Assignment Index Volumes" and "Patent Assignment Digest," in National Archives, College Park, Md.

Note: Patents include all those issued to each inventor through 1865; internal patents include those in table 3.1 and others not captured by that table's keyword methodology.

Table 3.3. Location of Patenting by Period (percentages)

	New England	Mid-Atlantic	South	West	Foreign	Cities
Textiles						
1790–1835	51.3	39.1	4.4	4.7	0.5	28.8
1836–65	63.4	26.0	2.0	4.2	4.3	42.8
Steam engines						
1790–1835	17.6	62.1	10.4	7.1	2.7	61.0
1836–65	18.2	55.3	3.5	20.3	2.7	56.9
Printing presses						
1790–1835	46.3	53.7	0	0	0	90.2
1836–65	29.6	53.1	3.1	12.8	1.3	70.9
Clocks and watches						
1790–1835	56.0	40.0	4.0	0	0	38.0
1836–65	43.2	37.5	3.4	11.9	4.0	44.9
Woodworking						
1790–1835	42.2	48.9	5.6	3.3	0	25.6
1836–65	37.8	41.1	3.1	17.7	0.3	45.1
Firearms						
1790–1835	29.6	44.4	13.0	13.0	0	33.3
1836–65	37.5	44.0	4.5	10.3	3.8	56.4

Sources: See table 3.1.

Note: Cities had over 10,000 people in 1850, excluding foreign cities. Regional shares of early patents differ from those cited in chap. 2 because the range of patents surveyed was narrower, especially in woodworking, which excluded sawmills.

Table 3.4. Average Patenting by Occupation and Period

	Textiles	Steam Engines	Printing Presses	Clocks	Wood-working	Firearms	All
Inventors, 1790–1835							
Number	298	154	32	36	83	52	655
Average patents, 1790–1835	1.31	1.19	1.28	1.39	1.08	1.06	1.24
Average patents, 1836–65	0.15	0.03	0.19	0.25	0.16	0.02	0.12
Inventors, 1836–65							
Number	580	519	137	128	310	493	2,167
Average patents, 1836–65	1.44	1.20	1.61	1.30	1.20	1.64	1.40
Occupations, 1790–1835							
Number with occupations	52	44	21	12	10	10	149
Machinists (%)	59.6	40.9	52.4	8.3	40.0	20.0	45.0
Science and invention (%)	1.9	9.1	0	0	10.0	10.0	4.7
Other manufacturing (%)	19.2	22.7	42.9	83.3	30.0	50.0	31.5
Trade and service (%)	19.2	27.3	4.8	8.3	20.0	20.0	18.8
Agriculture and extraction (%)	0	0	0	0	0	0	0
Networked (%)	62.0	31.8	76.2	88.9	55.6	28.6	54.3
Nonnetworked (%)	38.0	68.2	23.8	11.1	44.4	71.4	45.7
Occupations, 1836–65							
Number with occupations	212	219	76	58	81	146	792
Machinists (%)	47.2	50.7	39.5	15.5	44.4	26.7	41.0
Science and invention (%)	4.2	20.1	19.7	5.2	4.9	12.3	11.7
Other manufacturing (%)	41.0	17.4	34.2	69.0	45.7	47.9	37.6
Trade and service (%)	6.6	10.5	6.6	10.3	4.9	9.6	8.3
Agriculture and extraction (%)	0.9	1.4	0	0	0	3.4	1.3
Networked (%)	64.5	21.1	49.0	69.0	42.1	32.8	42.1
Nonnetworked (%)	35.5	78.9	51.0	31.0	57.9	67.2	57.9

Sources: See table 3.1; see also city directories and census reports, 1850 and 1860, accessed at *Ancestry.com.*

Note: Occupations were determined from directories for over 60 cities and from manuscripts of U.S. censuses of population in 1850 and 1860. Network inventors included only those listed in city directories.

while trade and service occupations declined. Occupations with general technological knowledge (e.g., machinists, science, and engineering) or particular craft knowledge remained central.[4]

One other continuity was essential to technological dynamics. Inventors continued to be embedded in industry networks that communicated new knowledge. Network patentees, whose occupations made them potential users of new techniques or producers of new capital goods, constituted over two-fifths of in-

ventors in both periods. Because network inventors averaged more patents, they received 67 and 58 percent, respectively, of all internal patents in the earlier and later periods.[5]

The persistence of inventive patterns—large numbers of inventors from technologically knowledgeable, networked occupations receiving a patent or two—suggests that the ongoing mechanization continued along earlier paths. Earlier inventors, who received one-tenth of their patents after 1835, supplied some of the continuity, but the vast majority of post-1835 inventors were new. The persistence of patenting behavior does not imply that innovation paths were unchanging. For network organization may have changed as paths matured. Because of rising patenting by foreign residents and by engineers and applied scientists—changes from abroad or above—innovation paths may not have remained as self-contained. Many paths faced similar limits in designing and making machines; solutions may have integrated innovation paths. Ongoing innovation may have required that innovation paths themselves evolve.

Textiles beyond the Industrial Revolution

The census of 1860 was unequivocal about leadership in antebellum industrial development when it stated, "The growth of the culture and manufacture of cotton in the United States constitutes the most striking feature of the industrial history of the last fifty years."[6] The statement's symmetry is intriguing: the culture of cotton was the locus of plantation slavery in the South, and its manufacture was the leader of factory capitalism in the North. Cotton was central to the divergent paths of the protagonists of the war that was about to engulf the country.

Textiles was one of the largest and most pervasively mechanized U.S. industries in the 1830s, and it remained so in 1860. Having originated through diffusion and developed through innovation, it continued to evolve through the same combination. Textile firms, textile machinery firms, and the machinist occupation continued to structure its evolution but in somewhat different ways. The patent system, consulting engineers, and publications came to provide knowledge, which could have reduced the importance of industry networks.

National cotton textile output surged from about 230 million yards in 1831 to 1.15 billion in 1860, and cotton spindles grew almost as rapidly. New England increased its output share from 62 to 74 percent even as its cotton cloth growth slowed from a remarkable 15 percent annually from 1815 through 1833 to a still-rapid 5 percent from 1833 to 1860. National output growth came largely through

increasing firm size. The number of establishments did not change from 1840 to 1860, though large firms replaced smaller ones. The once-remarkable 5,000 spindles in Lowell mills became more the average; the five biggest Lowell corporations averaged 60,000 spindles in 1858. Mills relied increasingly on purchased machinery but still retained machine shops. In 1831 one Connecticut firm estimated that maintaining its equipment required one worker for each 1,000 spindles, though superior equipment required relatively fewer machinists.[7] With machinists and mechanically adept superintendents, textile mills remained a locus of technological knowledge.

The textile machinery industry also grew. The first accurate count in 1860 listed 192 establishments employing 4,800 workers to make cotton and woolen textile machinery valued at $4.9 million.[8] About 75 made textile machines; the rest of them made parts such as shuttles, reeds, and card clothing. Reliable national measures did not exist before then, but the number of Massachusetts textile machinery firms did not increase from 1831 through 1860, though workers almost doubled, and output value more than doubled.[9] The Massachusetts–Rhode Island nexus central to the origin of the industry continued to dominate, with almost two-thirds of U.S. employment and output in 1860.

As machinery production within mills declined after 1830, machinery firms became more central. Locks and Canals, which in 1845 became the Lowell Machine Shop, supplied whole plants, as did William Mason, Alfred Jenks, and a few others. Many firms specialized in a few machines. Firms sold widely, often in repeat orders. William Mason sold 60 percent of his spindles to 19 customers, and over 60 percent of the sales were reorders.[10] Specialized input suppliers sold card clothing, bobbins, shuttles, and reeds. Contracts and mobility spread specialized knowledge among mills, machinery firms, and suppliers.

Workers completed the textile network. Trained in mills and machinery firms, workers were highly mobile, particularly the machinists central to innovation. Only 5 of 31 machinists employed by the Boston Manufacturing Company in 1817 continued to work for the firm in 1823. Locks and Canals records list 828 workers employed at some time between 1838 and 1845, over three-quarters by independent contractors and the rest by the company directly. About 40 percent had left the company by 1845, many with valuable knowledge. A few went to machine shops in other Lowell companies, but the bulk simply left. Machinists moved among textile and textile machinery firms. William Burke spent two decades working for Ira Gay, Locks and Canals, Nashua Manufacturing Company, Lowell's Boott mills, and Amoskeag Manufacturing Company before the Lowell Machine Shop hired him as superintendent in 1845. Skilled workers at times

formed their own firms. Among large machinery firms listed in the 1860 census manuscripts, Alfred Jenks and the Lowell Machine Shop originated early, Paul Whitin and Sons began by designing machines used in its mill, and William Mason had worked in a series of machine shops.[11]

Changes in industry networks helped overcome knowledge deficiencies. Machinery firms spread leading techniques. So did consulting engineers, a specialty originating, as Adam Smith predicted, with the growth of the market. Led by Charles T. James, consulting engineers designed and equipped factories. Trained in Rhode Island mill shops, James set up small Connecticut mills and in 1834 was hired by Slater to modernize his steam-powered mill. James became an advocate of steam mills, and in the late 1830s he equipped and operated steam mills in the coastal city of Newburyport, Massachusetts. He then became a consulting engineer and designed 30 steam mills through 1853, mostly on the coast, with 7 percent of the nation's spindles.

Factors outside industry networks widened knowledge flows. The patent system played a bigger role after 1835. Unlike most early techniques, including water frames, mule spinning, and many carding machines, major new techniques after 1835 were all protected by U.S. patent rights. The 1836 patent law reform increased the security of property rights, and assignment became common.[12] New publications, such as Abraham Rees's *Encyclopedia* and James Montgomery's *Carding and Spinning Master's Assistant,* included current knowledge about textile techniques. The commissioner of patents' annual reports described patents in some detail. Technical journals, including the *Journal of the Franklin Institute* and *Scientific American,* listed patent specifications and discussed major trends, though textiles received less space than many other innovations.

Network and extra-network institutions combined to diffuse techniques from abroad. One might imagine that diffusion was a once-and-for-all process, ending when the follower caught up. For textiles this was not so; industrialization began and evolved through foreign and indigenous knowledge and did so largely through the same institutions. Many innovations migrated soon after inception, most significantly the self-acting mule. For Marx it "opened up a new epoch in the automatic system" and was invented "for the sole purpose of providing capital with weapons against working-class revolt."[13] Its inventor, Richard Roberts, was a Manchester machine tool producer trained in the shops of John Wilkinson and Henry Maudslay, respectively the principal inventors of the boring machine and the British engine lathe. Roberts developed his mule at the request of a committee of textile manufacturers seeking to displace militant hand mule spinners. He received a series of patents from 1825 through 1834, when the self-actor pow-

ered 300,000 spindles. James Smith invented another self-acting mule for coarse goods in the mid-1830s. Both machines were introduced to the United States by the early 1840s. A Fall River textile mill owner and superintendent secured Roberts's agreement to smuggle prototypes out of England and in 1841 patented the mule in Roberts's name. A firm was set up to manufacture self-actors, and licenses were issued to Pitcher and Brown; by 1847 Roberts machines drove 180,000 U.S. spindles. Matteawan introduced the Smith mule in the Hudson Valley; it smuggled a model into the United States, patented it in Smith's name in 1838, produced mules itself, and licensed production to Lowell and Amoskeag machine shops.[14]

Similar processes improved machinery to produce textile machines, though patenting was less important. As knowledge of Maudslay and Wilkinson lathes spread, shops used industrial lathes equipped with slide rests and change gears from the 1820s. The planer, which cut flat metal surfaces and replaced the hand chisel, was imported in the late 1830s. A series of British inventors developed planers from the 1790s, including Roberts. Locks and Canals owned three planers in 1838. It also imported a drilling and boring machine from Joseph Whitworth, the world's premier mid-nineteenth-century machine tool maker. Such machine tools, quickly copied by U.S. firms, improved precision and hence the durability and quality of textile machines. By constructing lathe beds more precisely, the planer increased the accuracy of turned products and extended lathe usage.[15]

Textile and textile machinery firms also introduced the French turbine. The engineer Benoit Fourneyron invented the turbine in the late 1820s and adapted it to power mills in the early 1830s. By 1840 its superior efficiency in using the energy of falling water—estimated at 70 to 78 percent in large turbines—was widely documented in the United States, notably in the *Journal of the Franklin Institute.* The Fall River textile mechanic George Kilburn built a Fourneyron turbine in 1844, which became the principal product of E. C. Kilburn and Company. Ably determining appropriate turbine sizes and installation methods, Kilburn sold dozens of relatively inexpensive, small- and medium-sized turbines to New England textile mills and some to firms in other industries and regions. Lowell led in turbine usage. The Boston civil and hydraulic engineer Uriah Boyden creatively adapted the turbine to the needs of large Lowell mills, designing machines rated up to 700 horsepower, perhaps in consultation with Kilburn. Turbines then spread to high-horsepower sites, increasing the power delivered by as much as one-third. The turbine designs of Emile Geyelin, who worked for a principal French engineering firm, improved waterpower efficiency in the Middle States.[16]

Diffusion from abroad took new forms. Whereas immigrating workers and inventors transferred most early Industrial Revolution technology, now U.S. textile machinery firms sought out and imported European textile technology and machines. They also transferred British metalworking methods, supported by recently formed British capital good firms. Foreign inventors patented more (though never more than a few percent of patents), and American firms became the agents for and assignees of British inventors.[17] Worker mobility and machine purchase might have spread usage anyway, but patenting sped diffusion by providing incentives for British inventors to supply knowledge of machine design and production. Moreover, after 1830 textile improvements rested on learning from sectors outside from the cotton industry. Machine tool and turbine inventors learned from many industries and used inventions just as widely. Some used knowledge of applied science and mechanical principles. Textiles benefited greatly from such spillovers.

Techniques could spread from other countries or regions without domestic invention or even preclude such invention. This was largely the case when textile factories spread to the South after the Civil War. It was not so in the North. Many of the capabilities and incentives that sustained diffusion—production and design skills and ample machine sales—also fostered invention. Spinning was one locus. The Pawtucket textile machinist Ira Gay designed a self-acting mule in 1823, which he patented in 1829. Pitcher and Gay and successor companies built it. It never diffused widely and was supplanted by Roberts's mule, especially as produced by Wilkinson's and Gay's protégé James S. Brown. William Mason invented the only American machine to compete with Roberts's mule. Mason was hired as a foreman of a Taunton, Massachusetts, machine shop to develop and build ring spinners and then self-acting mules, only then just crossing the Atlantic. A first model competed effectively with the Smith mule. Running his own firm in the early 1840s, Mason developed a more automated, power-saving model. His firm built about a quarter of the spindles installed in the United States from the mid-1840s through 1861, three-quarters of which were self-actors.[18]

American inventions would be decisive in the long run. The operation of the flyer, the part on the top of the spindle that twisted the yarn, limited the speed of the Arkwright frame. Among many failures two inventions overcame the limit. Charles Danforth's cap spinner ran 30 to 40 percent faster than the Arkwright frame. Trained in spinning near Taunton and brother to George Danforth, who developed roving machines, Charles worked at Matteawan, developed his machine at a Ramapo, New York, mill, and produced it in Paterson, where he came to own a leading textile machinery firm. The ring frame brought flyerless spin-

ning. Its principal inventor, John Thorp, invented a power loom in Providence in 1812 and moved to Taunton to build and sell looms. He took out a series of ring-spinning patents in 1828 and 1829, which Mason and others perfected. Mason sold ring frames with about 200,000 spindles through 1861, and four other Rhode Island and Massachusetts firms joined the field by 1850. Even the technologically conservative Lowell Machine Shop shifted to ring frames, which made up over two-thirds of its spinning machine output in 1865. Ring spinning would dominate U.S. textile production by the end of the century, in contrast to the British commitment to mule spinning.[19]

U.S. inventors continued to improve weaving. Ira Draper and his son George developed loom temples, which held the cloth at proper widths, enabling one operative to run two looms. William Crompton and his son George brought the power loom to fancy goods. Taunton's Crocker and Richmond hired the father, an English hand loom weaver and machinist, to build fancy looms, which used many harnesses carrying different threads. He succeeded, used his looms, and had a Worcester machinery firm build them. His son improved the machine and established a Worcester firm that, with a neighboring firm, dominated fancy loom production. Others extended the application of power looms, including Erastus Bigelow, a Worcester County cotton mill worker who invented power looms for quilts, coach lace, and, most important, carpets.[20]

Each of these inventors was involved in textile networks that supplied knowledge of techniques, their problems, and possible solutions. Growing textile-machine production and sales spread knowledge and increased incentives to invent, contributing to the tripling of textile patents from 1836–45 to 1856–65. Over three-fifths of inventors had network training. William Mason illustrated the many roles that networks played. The son of a Connecticut farmer-smith, Mason was enmeshed in the factory textile nexus from age 14, when in 1822 he and his brothers found work in a cotton mill. An able mechanic, Mason set up spinning machinery in a new mill and was apprenticed as a machinist. Footloose, as were many machinists, in 1828 he left to become a machinist near Utica, New York. His previous employer hired him back to design diaper and tablecloth looms. Mason contracted to make diaper looms for a nearby firm, which recommended him to Asahel Lanpher, who made a full line of machinery in a Killingly, Connecticut, machine shop. In 1833 Lanpher employed him to develop a ring spinner, invented by Thorp only five years earlier but already improved by two Killingly inventors. He simplified the Thorp frame and sold ring spinners to area mills. At a mill owner's recommendation Crocker and Richmond, which had customers in the Killingly area, brought Mason to Taunton to perfect and sell ring spinners

in 1836. At Crocker and Richmond and his own firm, Mason perfected the ring spinner and developed his self-acting mule, making him a leading figure in the two central spinning innovations after 1830. Mason played the same supportive role for others. He employed William Crompton to develop a fancy loom and taught other inventors.[21] He used experience developing machinery in a series of firms to form his own company. In other sections of the country his considerable mechanical talents might have steered him toward steam engines or agricultural machinery, but in the area of early Slater mill expansion, it led him into mills and textile machine shops.

Knowledge of textile techniques was channeled through labor and product markets; because the markets were geographically concentrated, so were knowledge and invention. Patent systems, courts, publications, and industrial exhibitions distributed knowledge more widely but were insufficient to enter production. The *Journal of the Franklin Institute* noted that James Smith's mule could not be constructed from drawings alone.[22] Such media were in principle national in scope but in practice were more regional. The market for patent licenses was located near potential users, as were infringement cases; they connected Massachusetts more closely to Rhode Island or even Lancashire (where many Americans tried to import British patents) than to Iowa or Mississippi.

The concentration of patenting in New England makes sense in this context. Home to three-quarters of the nation's textile machinery output in 1860, the region increased its share of patents from 51 percent before 1836 to 63 percent after (see table 3.3). New England residents averaged three times as many patents as the national average before 1836 and 5.6 times as many over the next three decades, while western and southern states together fell from 18 percent of the national average before 1836 to 11 percent after.

The importance of proximity to industry networks may be clearest where they had little existence. The West had many machinists by midcentury, consumed large amounts of textiles but had few textile factories. Its few percent of textile patents focused more on family use. From 1846 through 1865 states outside the Northeast took out seven-eighths of patents for family use, led by Iowa and Indiana, with 13 patents. Such invention had its own goals and in some cases its own inventive community, including one concentrating in adjoining counties in south-central Iowa.

Foreign residents invented a little more after 1835, reflecting greater diffusion via patenting. Immigrants played a considerably larger role in U.S. patenting. Census manuscripts list the place of birth for U.S. residents in 1850 and 1860. Of 170 inventors with known birthplaces, 24 percent were born outside the United

States, overwhelmingly in Britain and Ireland. Almost half of the foreign-born with known occupations were textile producers, and another eighth were textile machinists.

Network inventors were especially important for ongoing innovation. For the 1790–1865 period five-eighths of the 174 inventors with sufficiently detailed occupations were employed in textile networks. They were more persistent inventors, averaging 2.6 textile patents, compared to 1.6 for other inventors, and so received three-quarters of patents. Textile machinists made up 59 percent of network inventors and received 78 percent of their patents. A higher share of network inventors assigned patents to others than did other inventors. Other network inventors built and sold machinery using their patents rather than assigning them, including spinning inventors Charles Danforth, William Mason, and James S. Brown and loom manufacturers George Crompton and George Draper. Some firms using their own patents also licensed rights to others. In 1832 Locks and Canals licensed Danforth's patent for $3,500 and 50 cents per spindle; in the next decade it licensed rights to make Smith and Mason self-acting mules.[23]

Innovation extended beyond patenting. Mill owners reorganized production to increase productivity. In a Lowell mill operating with the same equipment, productivity grew by 2 percent per year from 1839 through 1856. Some of the increase resulted from equipment modifications, both generated within the plant and transferred from outside, and much emerged from learning how to use equipment more effectively. Because learning with given equipment declined over time, sustained long-run productivity growth depended on equipment improvements.[24]

U.S. invention improved machine production. Just Wilkinson's industrial lathe made textile machines, so James S. Brown improved that lathe by augmenting the versatility of the slide rest. He then developed a boring machine with the precise purpose of "boring the inside groove, fliers for double speeders," which made roving machines more accurately. Later Brown adapted gunstocking lathes to form cotton machinery rolls and designed gear cutters and other equipment used in his shop. Textile machinery firms improved their capacity to make durable, complex machines, as reflected in machine tool inventories. In 1829 the Saco Manufacturing Company used about 60 lathes and related machine tools, mostly small and run by hand. In 1850 its successor's inventory listed 165 machine tools, including 77 engine lathes, 5 of which were 20 feet long; 48 hand lathes; 10 planers, one 26 feet long; and several drilling machines, bolt machines, and gear cutters. Firms that had made their own machine tools now purchased some.[25]

Many invented to power textile equipment. The most important waterpower innovator was James Francis, the superintendent of Locks and Canals. Francis

purchased patent rights to Boyden's turbine, which he studied and improved. He undertook a series of turbine experiments that, according to one engineer, increased Lowell's power capacity by one-quarter. Francis's book *Lowell Hydraulic Experiments* described the subtleties of turbine design. His success initiated a sequence of improvements. The benefits were so clear that 47 surveyed New England cotton mills employed over one-third more turbines than traditional waterwheels in 1866.[26] Textiles also used the most advanced steam engines. Already in 1838, 110 engines powered textile mills. Growing numbers of sophisticated New England firms combined leading textile machines from Mason and others with Providence-built high-pressure steam engines designed to provide power and control, including those of Fairbanks and Bancroft and their remarkable protégé George Corliss.[27] Textiles became a center of debate about whether the best engines could outcompete the best turbines.

Textile mechanization united British textile machinery and machine tools, Continental power innovations, and American improvements in textile machines, machine tools, and power. Textile machinery became highly specific, imposing barriers to entry for outsiders. It followed a clear internal dynamic; practitioners applied industry-specific knowledge to solve specific problems. Mechanization also relied on innovation in other sectors. It has been suggested that Mason emulated the motion of the planer in the reciprocating racks of his mule's winding motion. Improved turbines, engines, and machine tools developed largely outside textiles. Important textile machinists acquired their skills outside the industry, including the Saco Water Power Company's superintendent, Otis Holmes, who had been trained at the Springfield Armory; George Crompton, trained at Samuel Colt's armory; and the many machinists who made locomotives, machine tools, cotton gins, and fire engines when Lowell, Amoskeag, Mason, and other firms diversified.[28] Textiles followed its own path, but the path was informed by developments in many other sectors. Paths of industrialization continued in part by building on one another.

The Penetration of Steam Power

Writing in 1805, Oliver Evans predicted that among useful "principles of Nature," steam would "perhaps soon be esteemed first in the class."[29] Except for the steamboat, its promise in the United States was largely unrealized 30 years later. Diffusion had been slowed by deficient engine design and the modest metalworking capabilities of a preindustrial economy. By the 1830s the ground had been laid to overcome these obstacles, partly at Evans's doing. The knowledge and organiza-

tional forms established in the first third of the century, within a context of economic and engineering change, propelled steam power's expansion in the middle third of the century.

The steamboat expanded rapidly after 1835. Boats on western rivers quadrupled through 1850 and grew even faster in tonnage, and other regions grew more rapidly (table 3.5). By 1860 the stunningly rapid penetration of steamboats had been substantially completed. Steam power in manufacturing expanded 45 fold from 1838 to 1870. The pace was highest through 1850, but the absolute increase was greater afterward. Average horsepower rose from 18 in 1838 to 30 in 1870. From two-thirds of the horsepower of steamboats in 1838, stationary engines almost doubled that of boats in 1870. Steam power grew much faster than did U.S. manufacturing, which increased employment by 165 percent from 1840 to 1860. By 1870 steam engines supplied 52 percent of the country's manufacturing power, a dramatic increase from the tiny share in 1838.[30]

While engine usage surged, its composition by industry remained remarkably stable. Engines continued to be used for the same cutting, grinding, and rolling operations described in Evans's patent. Lumber increased its share of manufacturing engines from 24 percent in 1838 to 30 percent in 1870, flour milling rose to 13 percent, and iron mills and casting stood at 8 percent. Material processing remained key; the engine shares of textile, machinery, and printing industries actually declined somewhat, even as engines more suitable to their needs arose. As material processing expanded, steam power grew fastest in the Midwest and trans-Mississippi West, which increased the regions' share of engines from 9 percent in 1838 to 42 percent in 1870.[31]

Engines continued to be sold as capital goods to custom order by firms producing a wide range of products. Engine making involved specialized knowledge that even machine shops did not easily acquire; few firms made their own engines after 1840. Engines varied in horsepower, boiler size, gearing requirements, and cost. A few firms built for the market; from the mid-1840s William Burdon carried as many as 100 engines in stock, ready for shipment.[32] Firms tried to design standard sizes and to adapt them to meet users' needs, and patterns were so important that large firms housed them in separate buildings. Still, machines were typically built when ordered so that there were modest scale economies in production, though more in design.

Virtually no firm concentrated only on steam engines. Firms typically produced engines, boilers, and gearing, along with machines for industries as varied as sugar, textiles, and agriculture. In the 1860 Boston business directory, for example, the large, successful Boston engine maker S. E. Chubbuck highlighted its

Table 3.5. Steam Power, 1830–1870

	1830	1838–40	1849–50	1859–60	1868–70
Engine usage					
Steamboat					
Tonnage, U.S. (in 1,000s)	62	183	372	641	698
Tonnage, West (in 1,000s)	29	84	142	163	229
Horsepower, U.S. (in 1,000s)	—	57	305	503	624
Manufacturing					
Engines, number	200	1,400	8,600	25,600	40,200
Engines, horsepower (in 1,000s)	—	27	187	621	1,216
Engine production					
Firms	—	273	—	205 (surveyed)	663
Average output	—	5.8 (cumulative)	—	17 (surveyed)	12.6

Sources: Louis C. Hunter, *Steamboats on the Western Rivers* (Cambridge: Harvard Univ. Press, 1949), 33, 565, 643; Lance E. Davis, Richard A. Easterlin, and William N. Parker, *American Economic Growth: An Economist's History of the United States* (New York: Harper & Row, 1972), 485, 488; Hunter, *Steam Power,* 72–79, 110, 366; Jeremy Atack, Fred Bateman, and Thomas Weiss, "The Regional Diffusion and Adoption of the Steam Engine in American Manufacturing," *Journal of Economic History* 40 (1980): 282–85; U.S. Treasury Department, "Steam-Engine" 25th Cong., 3rd sess. (serial no. 345), H. Doc. 21. 1839; U.S. Census Office, *Census of the United States (1870),* vol. 3: *The Statistics of the Wealth and Industry of the United States* (Washington, D.C.: Government Printing Office, 1872); U.S. Census Office, Manufacturing Manuscripts from the Eighth Census, 1860 (National archives and in state archives in Conn., Del., Md., N.H., N.J., N.Y.).

Note: Steamboat tonnage for 1868–69 is readjusted for consistency with pre-1865 measures. U.S. horsepower in manufacturing in 1850 is estimated by multiplying the number of engines by an average horsepower assumed intermediate between levels in 1838 and 1860, which is much less than Hunter's 1850 estimate of 450,000 horsepower.

steam engines and boilers but also included "shafting made, pulleys and hangers furnished . . . Machinery of all kinds, such as saw, planing and grist mills . . . Tanneries fitted complete with all modern machinery . . . Breweries furnished with Engines, Boilers, or Horse-Power, Mash-Tubs, Malt-Mills, Pumps, Piping . . . construction and putting up of Steam Heating Apparatus in Hotels, Factories and Dwelling Houses."[33]

Spreading in virtually as many directions as there were kinds of machinery and related apparatus, engine makers had not separated themselves from general machine shops, as manuscripts of the 1850 and 1860 censuses document. Published censuses did not identify the products of firms, but entries in census manuscripts did. In counties with substantial machinery output, 205 firms made steam engines or boilers in 1860, one-quarter of all sampled machinery firms. Most firms detailed their products. One-third of them listed one kind of machine, though it was often accompanied by boilers, shafting, and castings. Two-

thirds of the firms, with seven-eighths of workers, made a variety of machines, including machine tools, sugar mills, boats, printing presses, agricultural and mining machinery, flour and sawmills, and locomotives. Much the same was true in 1850.[34]

Firms continued to target local and regional markets; only the South had significant net engine imports. Engine production moved westward with usage; the Midwest and trans-Mississippi West increased their output share from 13 percent in 1838 to 35 percent in 1870. Firms remained urban but spread among cities. The eight leading cities made two-thirds of the engines in 1838 and one-third of the value of engines and boilers in 1870. Firms usually negotiated directly with users. The correspondence of Providence engine maker Fairbanks and Clark (later Fairbanks and Bancroft) documented 60 engine sales from 1838 through 1846. Most customers located in New England, but several came from Cuba and the U.S. South. For each order the firm presented proposals to purchasers or their agents. In some cases the proposals listed machinery run by the engine, such as a textile-finishing firm using eight printing machines, sprinklers, dryers, and lathes. Textile mills were its most important customers, including several equipped by Charles James, but it also sold to iron works, screw makers, machinery companies, and steamboat firms.[35]

As engines penetrated the market, annual firm output grew. In 1838 engine makers averaged 5.8 engines in operation. About half were made since 1835 so that firms averaged around 1 engine per year. The 663 firms making boilers and steam engines in 1870 averaged 12.6 engines in that year. Rising output per firm accounted for most engine growth, even as engine firms doubled from 1838 to 1870. The transition probably occurred by 1860, when firms listed in the census manuscripts averaged 17 machines sold at $2,200 each.[36] New firms had more diverse backgrounds than textile machinery firms, in large part because engine networks were more dispersed, involving thousands of engine users and producers spread across regions and industries. Publications supplied more knowledge than in textiles, including articles such as the *Journal of the Franklin Institute*'s tables on the relation of cylinder diameter, cylinder length, number of strokes per minute, and horsepower.[37] But engine making involved much tacit knowledge, and workers with engine expertise had a big advantage, especially when they also invented.

Steam engineering invention improved valve gear, power transmission, governors, and propulsion systems. Engine patents grew fivefold from the 1836–45 to the 1856–65 decade; navigation patents tripled over the same period.[38] Many inventors secured some success, including the two-fifths who assigned engine

patents to others, along with inventors, including George Corliss and Robert Stevens, who used but did not assign patents. Inventors located where they could learn, especially near engine firms. Mid-Atlantic States dominated, with 55 percent of engine and navigation patents, 45 percent of the value of steam engines in 1870, and 33 percent of engine usage.

Knowledge was easiest to acquire for engine builders, but it also spread in technical occupations employed to design, make, or apply machinery. Over half of post-1835 steam engine and navigation inventors with known occupations were machinists, and another fifth were engineers, draftsmen, patent agents, and related professions (see table 3.4). Machinists and scientific and inventive professions made up 71 percent of engine and navigation patentees, with 74 percent of all patents. Inventors from engine-using occupations included shipbuilders, carpenters, textile mill owners, and a wide variety of others.

Steam engineering patents had the highest share of machinists and engineers among early-industrializing sectors, but they had the lowest share of network inventors, only 21 percent after 1835. The network share was understated because most machinists, engineers, and engine users were excluded. Yet learning did occur in other ways, as Zachariah Allen's cutoff illustrates. Allen made woolen textiles in Providence, using waterpower but no steam. He also published widely about technology, including *The Science of Mechanics.* He was drawn to engines when lecturing at Providence's Franklin Society. In exploring the working of the engine, he discovered the problem of operating engines under conditions of changing loads "such as takes place when heavy machines are thrown into gear or disconnected." He experimented, and his patent embodied the solution.[39]

The most basic change was the Corliss engine. The well-built stationary engine of 1840 was effective and dependable, but it was neither fuel efficient nor provided regular motion. Many tried to overcome the limits. Mechanisms to cut off the inflow of steam part way through the cycle drove the piston with the expansive power of steam. Governors and flywheels compensated for variable engine output and changing power needs as machines were brought on- or off-line. But neither problem had been solved by the late 1840s. Corliss's variable cutoff mechanism quickly and automatically modified the point at which the engine cut off the flow of steam into the cylinder in a way that substantially increased the regularity of power and reduced fuel consumption. In the opinion of Robert Thurston, an outstanding steam engineer and son of a Corliss competitor, Corliss had designed "the most famous steam engine that has appeared since the time of Watt."[40]

Corliss's experience shows how much had changed since Evans invented. Evans had little support in inventing, developing, selling, and producing his engine.

Corliss benefited on each score. Employed as a storekeeper in a town north of Albany, he invented a boot-sewing machine. He went to Providence to commercialize his invention. The development of Providence since Slater's time had a decisive effect on Corliss's career. Still a major textile and textile machinery producer, Providence also had become a center of machine tools and steam engine production, led by the Providence Steam Engine Company, one of the biggest engine builders in the country in 1838, and its successor, Robert L. Thurston and Company. Textile and engine interests intersected in Slater's steam mill, the steam mill movement, and efforts to develop engines suited for the large-scale mills.

Corliss came to this cauldron of mechanical activity in 1844. He took his sewing machine to the engine makers Fairbanks and Bancroft, who wisely convinced him to abandon it but offered him a drafting job. In a letter to Corliss, Bancroft lobbied: "I should have no fear of your succeeding in a business connected with Steam Engines & other machinery. You would find some trouble at first no doubt in mastering the thousand and one different ways of coming at the same thing—but for a person who sees the 'why' of a thing as readily as you do, the trouble would soon change to pleasure." Within three years Corliss conceived his cutoff mechanism and became a partner in Corliss, Nightingale and Company. His first engine was a 260-horsepower machine used in a Providence textile finishing firm. His design was superb, but Providence supplied the technical knowledge and contacts with users, workers, and financiers that brought success so quickly. Like Evans, Corliss is said to have consulted a local mathematics and science professor.[41]

Corliss made the best of his promising start. He marketed by offering the choice between purchasing his product at a fixed price or and paying an amount equal to its fuel savings for a certain period. In textile mills his engine saved fuel—he claimed by 30 percent—and improved the regularity of power, which reduced thread breakage and enhanced the quality of cloth. Corliss's largest market was textiles, but he also sold to metal-rolling, tool-making, publishing, and other industries. Starting with local markets, he expanded into much of the East and occasionally elsewhere. Corliss built 250 engines by 1858 and 480 by 1863. Yet he did not specialize solely in engines; in the early 1850s his engines provided only 30 percent of the firm's revenue.[42]

As the extensive patent litigation shows, Corliss was not alone in developing automatic cutoffs. Two Providence industrialists had similar inventions. One was Zachariah Allen, whose efforts to get a local engine-building firm to commercialize his 1834 patent failed. The second was Robert Thurston of the Providence Steam Engine Company. Thurston recognized that stationary engines could use Frederick Sickels's cutoff, invented for steamboats, and purchased rights to use it

1845.[43] We do not know that Corliss copied or even knew about the other inventions; the similarity points to the widespread recognition of the need for a cutoff and the overlapping solutions to the problem.

Innovations occurred on other fronts. By 1850 steamboats often utilized the expansive power of steam. Some engines replaced water with air, without much success. The compound engine driving ocean steamships came from abroad. New cutoffs, including Charles Porter's governor, regulated machines more precisely. Porter's high-speed engine greatly increased piston speed and hence horsepower for any cylinder size. Boiler patents grew from 30 in the 1840s to 105 in the 1850s and 231 from 1860 through 1866. Robert Stevens and John Ericsson developed screw propellers for boats.[44]

The expanding engine sector was a center of attraction and education for inventors. Corliss made good use of his education in engine shops. Frederick Sickels, like Corliss a physician's son, was a New York machinist trained in James Allaire's marine engine works, with a focus on cutoff mechanisms to economize fuel on steamboats. Robert L. Stevens grew up with steamboats. He helped design and construct the *Phoenix,* a competitor to Fulton's *Clermont,* and piloted it from New York to Philadelphia in the first steamboat sea voyage. Stevens patented an important engine cutoff in 1841 and improvements in boilers, propulsion systems, and boat design.[45]

Corliss's experience carries another important lesson for ongoing technological change. The engine's "outlandish and extraordinary" valve gear, in one British engineer's words, was so complex that many doubted its effectiveness and durability.[46] Accurate production was critical but would have been difficult or impossible with engine-building methods of 1830. Engine innovation rested on metalworking improvements that originated largely outside American engine making.

The well-equipped engine shop of 1830 had advanced far beyond Evans's Mars Works. Leading shops had improved casting skills, purchased rolled iron, and used boring machines and the industrial lathe, complete with a slide rest. But more was needed to make precision parts. Corliss's employer, Edward Bancroft, was one of the first to use the Whitworth metal-planer, which Locks and Canals sent him in 1838.[47] The combination of industrial lathe, planer, and boring machine enabled engine makers to bore cylinders and cut accurate curved and flat parts. New precision measuring instruments included the vernier caliper, which Joseph Brown made from the early 1850s.

Corliss used such innovations and developed others. Louis Hunter writes: "In the last analysis the preeminence established by Corliss in the engineering field

rested upon his outstanding capabilities in production. Although the originality of some features of his engine was strongly contested, even his opponents acknowledged his leadership in the building of large and complicated engines."[48] Corliss built machine tools, like most machinery firms in the late 1840s, and he improved machine tools at the same time he perfected his engine. He patented a gear cutter to make his engine's large, geared flywheels in 1849, the same year as his basic engine patent. He added gearing, lathes, and planers to his product line. Recognizing that engines were useless without transmission mechanisms, Corliss sold heavy mill gearing, including one "gear fly-wheel of 25 feet in diameter . . . weighing 64,000 pounds, turned, with cogs on the face cut with the accuracy of clock-work." Corliss's competitors were painfully aware of his innovative production methods. Robert Thurston felt the pressure keenly. According to his son, "Corliss beat us out of the market entirely . . . We tried to adhere to our old methods and to our old design, but we had to give them up; and the upshot of the whole matter was that the introduction by Corliss of that method led to a complete revolution in our methods of manufacturing steam-engines."[49]

By the Civil War the array of engine makers' machine tools included industrial lathes, planers, and drill presses. In Providence Joseph Brown developed universal milling machines and screw machines, and by 1867 Corliss used both. Boiler-making machines developed to drill holes and rivet. Leading engine makers across the country used such machinery to improve their products. Merrick's Philadelphia factory, which made heavy engines and machinery, used Nasmyth steam hammers and punching and riveting machines in forging and boiler shops, and its machine shop employed a variety of boring machines, lathes, drill presses, slotters, and planers, including one "believed to be the largest in the world."[50] As census manuscripts show, steam engine firms that also sold machine tools constituted one-third of firms listed as selling machine tools in 1850 and one-quarter in 1860, and engine makers were prime customers for William Sellers and other machine tool firms.

For steam engines, like other innovations, it is misleading to confuse the new with the normal. Corliss engines were vital for large-scale, sophisticated manufacturers, but they made up under 2 percent of all stationary engines with about 5 percent of total horsepower in 1860. Most stationary engines were small, high-pressure machines with rudimentary fixed cutoffs or no cutoff at all. Yet the multitude of small improvements in production accuracy added to engine efficiency and life. Early engines had notoriously short lives, but Corliss estimated that 93 percent of his cumulative output was still in use in 1863. Because over half had been constructed through 1858, engine life had lengthened.[51] Improved design

and production supported the growth of steam relative to waterpower. Likewise, though 1860 steamboats were larger, with considerably bigger engines, especially in the West they did not differ basically from the paddle wheelers of 1830. Efficiency grew with engine size, minor changes in propulsion systems, better boat design, and river improvements.[52] New screw propellers, compound engines, and iron ships only anticipated future dynamics and ones through which Britain would regain the lead.

Engines advanced largely from below, organized around networks of engine builders, engine users, and general metalworkers. An important part of the advance involved diffusion from other sectors that had improved machine tools, casting, and measurement techniques. Many U.S. engine and navigation inventors learned from abroad; almost one-quarter of 118 inventors with known birthplaces were born outside the United States, led by British residents. But except for machine tools, diffusion from abroad was less important than in textiles. Development from above was more important than in textiles. Engine inventors often read the literature on steam engineering, widely accessible from 1840. They knew methods of calculating power. Some had college training in the sciences. Many participated in mechanics' institutes. Much off-the-job learning was used in steam engineering practice, which came to transmit it. Technological innovation did not solve the problem of exploding steamboat boilers, but scientific organizations and the government contributed to a solution.[53] Steam power, unlike water turbines, did not rely on advances in science over the period. It developed through innovation by engine producers and users employing established science that had been internalized by steam engineering practitioners. Development from below also involved outside innovations, especially in metalworking. Without these innovations the subtle cutoffs around which so much litigation arose would have been clever contrivances without much use.

Toward a Universal Press

Tocqueville noted the "enormous circulation of the daily press" when visiting the United States in 1831. Publication expanded greatly over the next quarter-century, forming, in Joseph Whitworth's words, "an almost universal press," affordable to and availed by the working class.[54] Beginning in the early 1830s the penny press reduced newspaper prices and extended markets, much as in Britain. General-purpose periodicals, including ladies' and gentlemen's magazines, grew greatly in sales; 13 magazines published more than 100,000 copies of each issue by 1860.[55] Technological changes fostered the growth. In 1835 hand presses commonly

printed newspapers and books in relatively small runs based on slowly disseminating news. Twenty-five years later cylinder presses printed tens of thousands of newspapers using information the telegraph transmitted instantaneously. The transformation of printing was more radical than that of steam engines but was undertaken with greater continuity, led by established industry leaders.

As publication surged, so did the demand for printing presses. Because the size and production runs of publications varied greatly, so did presses. Samuel Rust's Washington press, practical by the late 1820s, became the leading hand press. An iron, toggle joint machine used in country newspapers with modest production runs, R. Hoe and Company sold it for $165 to $380 in 1854. Isaac and Seth Adams developed the most important bed and platen machine, which used steam power to raise the bed to a stationary platen. At 1,000 impressions per hour, it was used on newspapers and came to dominate the book trade; Harper and Brothers retired its hand machines and employed 30 Adams presses worth $75,000 in 1853. The power-driven, self-inking cylinder press pioneered in England by Koenig and Napier, in which a cylinder moved along a flat bed, became central for quantity work. After copying Napier's press, Hoe developed single- and double-cylinder versions, selling from $960 to $4,250, able to make 2,000 impressions per hour on each cylinder. Large-city newspapers required faster work, and in 1846 Richard Hoe developed a rotary press; its rotating, type-carrying cylinder formed up to 20,000 impressions per hour on four to eight smaller cylinders, and it automatically stacked the pages. Major U.S. and foreign papers adopted the machine. For cards and other small printed material, Stephen Ruggles and George Gordon developed self-inking, treadle-powered job platen presses. Inventors also devised means to ink and, imperfectly, to feed paper from rolls automatically.[56]

A great expansion of inventive effort, mostly within the United States, developed the new presses. Most improvements were patented. Press patenting grew over fivefold from 1826–45 to 1856–65 (see tables 3.1, 3.3, and 3.4). Invention continued to locate where presses were used and made, principally eastern cities, with the Midwest ascending late in the period. Machinists constituted two-fifths of inventors with known occupations, and another fifth were engineers, patent agents, and others with inventive and scientific professions. Printers and engravers led among other manufacturing occupations. Half of all inventors worked in printing networks as press makers, printers, engravers, or publishers. With 72 percent of patents, they propelled invention. A. B. Taylor, for instance, was Hoe's foreman before forming his own firm, and Andrew Campbell worked with Taylor before setting up a firm; Taylor and Campbell had the second and third biggest output in 1860. Competitors knew each other and even contracted with each

other; Adams did contract work for Hoe, and Hoe complained about the modest commissions when selling Adams machines.[57] That presses were widely observed and written about was insufficient to offset practitioners' advantages. Seventy-one percent of inventors used their own patents (including Hoe) or assigned them to others who could do so. Inventors known to have gained use by either route were more likely to continue patenting; their 3.7 press patents far exceeded the 1.5 for others.

Presses had to be accurately constructed to form thousands of impressions hourly for long periods, and accuracy was not easily secured. Hoe's records document prolonged efforts toward that end. In the 1830s it used slide lathes, drilling machines, and bolt-cutting machines of modest accuracy. Files were essential; Hoe ordered 65 dozen from England in 1835 and another 120 dozen in 1838. Hand planing was expensive and inaccurate. Needing radical improvements to make more complex presses, Hoe bought its first planing machine from England's James Nasmyth in 1839. Richard Hoe visited Edward Bancroft's Providence engine shop, where he observed a planing machine under construction, probably based on the Locks and Canals planer. He bought machine tools from Bancroft in 1841 and ordered planing machines in 1843 and 1845 for pieces larger than the Nasmyth machine could plane. He also purchased machine tools from the Novelty Iron Works in New York. Unsatisfied with the precision of American machinery, the company purchased slide lathes, other machine tools, and standard gauges from Joseph Whitworth, along with a British standard yard measure. By 1850, when its census entry listed 11 planing machines, 43 lathes, a foundry, and 3 steam engines, Hoe felt it could get superior machine tools from A. M. Freeland of New York.[58] The importance of such machine tools became clear where they were known but had not spread. In Columbia, Missouri, around 1847, Andrew Campbell stated that, when trying to turn the parts of a machine, "I had to make a lathe upon which to build them because there was no place within 125 miles where I could get a pound of casting or a slide rest lathe."[59] By 1850 firms in major cities no longer faced such problems.

Although many firms built presses, Hoe consolidated its leadership by combining invention, patent management, engineering quality, and outstanding production methods. Competitors criticized Hoe for copying others. But it improved the presses, most significantly in Richard Hoe's rotary, or "lightning," press and his paper-handling inventions. It purchased or licensed many patents. It sold the whole range of printer's machines, including specially designed steam engines for tight urban settings. It purchased whole companies, notably Adams's firm in 1859. In 1860 it sold the leading hand presses, the leading book presses, and the leading

newspaper presses; its 140 presses brought in $370,000, and its 425 workers made up over half the industry total.[60] By then new presses and complementary innovations in type forming, stereotyping, bookbinding, and the telegraph fostered the spread of books and the formation, in the North at least, of a universal press in which workers, educated publicly, could afford to participate.

Ongoing Revolutions in Time

Keeping time elicited continuing revolutions. The remarkable development of mass-produced wooden clocks in the first third of the century was supplanted by a revolution in brass clocks. Another revolution spread the watch. Like the wooden clock, later innovations brought time to the masses. New revolutionaries in tight networks led the upheavals. But the revolutions depended on outside transformations.

Brass clocks kept better time; anyone who could apply mass production methods of wooden clockwork to brass would gain competitive advantages. Yet brass clocks required greater precision than wooden clocks, and lower tolerances posed formidable production barriers. Chauncey Jerome, Seth Thomas, and Silas Terry—each trained in Eli Terry's shop—led the transition to brass clocks. They learned from another innovator of cheap brass clocks. Joseph Ives, also a Connecticut wood clock maker, designed brass clocks from 1822, culminating in the 1830s in an eight-day clock using rolled brass. Ives's clock design was little copied, but his use of rolled brass was, particularly in Chauncey Jerome's 30-hour rolled brass clock. Success rested on an innovation quite outside the industry. The Waterbury area had become a center making buttons, kettles, and other brass and copper products. Recognizing the importance of rolled brass, a method recently developed in Britain, Waterbury brass firms imported machinery and brass workers.

Brass-rolling and stamping methods and the practice of gauging wooden clocks proved indispensable to mass-produce brass clocks. Firms developed special-purpose machines to make standardized parts. Having become successful by the early 1840s, the Jerome Manufacturing Company made 130,000 clocks valued at $275,000 in 1850. Jerome failed in 1855, but others picked up the slack. Seth Thomas built his own brass-rolling and wire-drawing mill; his firm made 40,000 clocks in 1860. The Waterbury Clock Company, which in 1860 made 60,000 clocks and 10,000 movements, was one brass-using company formed by Benedict and Burnham, and it made full use of the parent firm's brass-making capabilities, coupled with special-purpose lathes, drills, and gear cutters. Clock makers

built some of their own machines and purchased others, relying on the skills of Connecticut workers and firms.[61] Firms needed a set of standards for brass products, especially wire. The Providence clock maker and instrument maker Joseph Brown formed standards and gauges in 1857, which the Waterbury Brass Association and other wire makers accepted.[62]

Mass-produced watches developed in a quite different way. Most watches had been imported, and watchmakers concentrated on repairs. Watchmakers and clock makers overlapped; success in mass-producing brass clocks was one inspiration to mechanize watchmaking. But watch factories developed outside the Connecticut brass area, principally around Boston, and found other inspirations. The key innovator, Aaron Dennison, was a jeweler and watch repairer who learned from Swiss and English watchmakers in New York. Knowledge of a failed watchmaking factory directed his attention to mass production, and he studied interchangeable-parts methods on visits to the Springfield Armory. After years of reflection, he pursued factory production in earnest in 1849 and within a decade formed a practical product on the verge of competitive success.

Dennison's idea was clear and persuasive: form "an interchangeable system" and manufacture "in large quantities." Realizing the idea proved much harder. He formed a partnership with the clock maker–entrepreneur Edward Howard. Dennison had to redesign his watch to produce it mechanically, reducing its duration to 36 hours. Misunderstanding the difficulties of uniform production, he could not purchase appropriate machine tools and instead took four years and much expenditure to develop watchmaking machinery. He underestimated the size of a mass production factory and had to build a second one at Waltham, thus providing the Waltham Watch Company its name. His production team combined watchmakers employed in the failed Pitkin watchmaking factory around 1840, two machinists who worked at the Springfield Armory, a screw maker trained in sewing machine construction, and English and Scottish dial makers and jewelers. Armory practice, transmitted particularly by Ambrose Webster, provided essential insights into the methods of uniform production, including standardization, gauging, and machining. But given the watch's size—300,000 of the smallest screws, with 240 threads per inch, weighed a pound—production had to be carried out differently. Dennison developed specialized stamping methods, lathes, drilling machines, and gear cutters. He and key workers traveled to England to acquire skills. The machine shop was especially important because machinists invented and produced the delicate production equipment.[63]

Success came, but not before the company was reorganized and Dennison was about to be fired. In 1860 the firm employed 200 workers to make about 15,000

watches worth $245,000. Output increased to 45,000 in 1865, stimulated by new models for soldiers. Invention removed sources of error and developed the first fully automatic machine tools, fostered by machine tool purchases from Brown and Sharpe. Yet truly interchangeable parts were beyond the firm's reach, especially for precise small parts, and would be for another 50 years. Hence, skilled labor with highly specific knowledge persisted in the machine shop and on the factory floor. Such skills powerfully shaped industry development. New firms had to acquire them, and every serious challenger was staffed by workers trained at Waltham. The Elgin National Watch Company, formed in 1864, became the most important competitor by using eight Waltham workers to superintend the plant, run various departments, and design and make machinery.[64]

Tight networks, located around a few firms in Connecticut and one around Boston, structured the mechanization of clocks and watches. The importance of networks is reflected in patenting patterns. Many key developments were not patented, including Jerome's production methods, Dennison's product design, and many watchmaking techniques. Waltham Watch had a significant portfolio of patents but did not believe they formed major barriers to entry.[65] Yet patenting was widespread and grew after 1855, when factory production grew rapidly (see tables 3.1 to 3.4). New England was the most important inventing region. Inventors trained in clock or watch networks constituted 70 percent of patentees after 1835, overwhelmingly clock or watchmakers. Only about one-quarter of inventors assigned clock or watch patents to others. But Dennison and others used patents in their own production, especially for new product designs or mechanisms. The ongoing revolutions in time combined learning in networks with learning from outside innovations in brass, firearms, instruments, and machine tools.

Mechanized Woodworking

In 1835 woodworking stood on the verge of a transformation. The revolution arrived over the next three decades, when the promise of earlier turning, planing, mortising, and circular sawing inventions was realized. Grasping the breadth of change, Joseph Whitworth wrote, "In no branch of manufacture does the application of labour-saving machinery produce by simple means more important results than in the working of wood." In 1853 he observed mechanized works making boards, shingles, flooring, doors, window frames, staircases, lasts, furniture, matches, and wagons. There had been precedents, but Whitworth noted that the British ship block revolution had stalled: "It must be confessed that the improvements which have been made have not been extended, as they might have been,

to ordinary purposes."[66] In the United States the revolution had reached the level of the ordinary.

In the middle third of the nineteenth century wood consumption, invention, and mechanization all expanded greatly. Wood consumption grew from 58 board-feet per capita in 1799 to 67 in 1829 and then quadrupled to 259 board-feet in 1859. Annual patents for wood lathes, planers, mortising, and tenoning grew from 0.7 from 1806 through 1825 to 6.6 from 1826 to 1845 and 16.3 over the next two decades. Mechanization spread widely. A 1790 sawyer or carpenter would have recognized the equipment of an 1835 sawmill or furniture shop, though details would have differed and machine prototypes would have surprised them. The 1860 sawmills, flooring or door factories, and furniture shops would have astounded them. Circular saws were common in saw and shingle mills, benefiting from design and production improvements to reduce wobbling. Planers spread in flooring and sash. Increasingly automatic lathes were specialized to make handles, spokes, lasts, and furniture. Mortising and tenoning machines abounded. Innumerable specialized machines applied to operations as diverse as making shoe peg blanks or bending wood for vehicle wheels.[67]

Mechanization occurred in largely separate processes; circular saw inventors rarely made planers or mortising machines. But the paths had important similarities. Machinists came to make woodworking machines. Spreading early planing machines had been difficult because users were small, and carpenters did not have machine-making capabilities. Machinists began to sell large numbers of woodworking machines in the 1830s. J. A. Fay was an industry leader. He patented tenoning machines in the 1830s and mortising machines later. Located initially in Keene, New Hampshire, he formed partnerships in Worcester; Norwich, Connecticut; and Cincinnati. In 1850 his Norwich plant employed 10 to make machines for sash, doors, and blinds. His 1856 catalog offered 56 machines, including various sizes of mortising machines, tenoning machines, scroll saws, matching machines, and chair-boring machines. In 1860 he employed 28. Others followed the same path. Census manuscripts in 1860 listed 23 firms concentrating on woodworking machinery, and other firms had woodworking sidelines. Some specialized in mortising and tenoning, others on planers (including a Worcester firm that made 100 of them), yet others on lathes. Saws were important for many firms, including R. Hoe, which recorded $150,000 in sales in 1860, and Henry Disston.[68]

Woodworking machines overwhelmingly developed in the United States, except in saw making, in which U.S. metallurgical capabilities were weak. Hoe and Disston recruited British saw makers. Machinists constituted over two-fifths of post-1835 inventors, using knowledge of mechanisms that carpenters did not pos-

sess (table 3.4). Two-fifths of inventors were in woodworking networks that linked machine inventors, producers, and users; they received 70 percent of the patents. Given the great variety of woodworking, it is not surprising that networks were diffuse, spread among regions—urban for planing but not sawmills—and divided by kind of consumer. But woodworking machinists were often in contact with each other, especially around Worcester and Cincinnati.

Practitioners were also linked by the patent system. The Blanchard lathe and the Woodworth planer were two of the most assigned antebellum inventions. Twice renewed by Congress, Blanchard's patent lasted through 1862, its 42-year life the longest of any U.S. patent. It spread from gunstocks to shoe lasts, spokes and carriage parts, plow and ax handles, and hat blocks. Although Blanchard produced lathes, his lathe spread more widely by assignment, often by area or use. Assignments in 1840 were mostly in New England and New York. By 1860 they extended throughout the Midwest and into Kentucky, Missouri, Nebraska, and Tennessee. Some assignees made and sold machines, but most used the lathe to make their own products. Blanchard provided technical expertise, helping to spread knowledge from one user to others. The Woodworth planer also diffused through assignments enforced by frequent lawsuits.[69] Many other patents spread in the same manner, including Ira Gay's planing inventions. Altogether about 45 percent of surveyed inventors assigned patents to others. Some chose different routes. C. B. Rogers, a one-time partner of J. A. Fay, used his patents in his own machinery firm. After initial assignments, Henry Stover did the same, buying back assignments and assigning patents to his own firm. George Page sold woodworking and agricultural machinery of his own design but also offered to sell territorial patent rights for all his patents.[70] Between assignment to potential users and usage within one's own firm, about 70 percent of woodworking patentees could have attained use.

The revolution in woodworking depended on new structures, especially the rise of machinery firms and markets for patent rights. Machinery producers advanced the revolution by transferring machine tools and metalworking procedures. Hoe, Gay, and others contributed by diversifying into woodworking. Expanding markets made the revolution possible, but innovating woodworking firms and their suppliers were needed to realize the potential.

Arming the Military and the People

Firearms present the puzzling case in which an earlier dynamic persisted even though principal actors and procedures did not. Firearms continued to develop

interchangeable-parts manufacturing after 1835 even as government contracting, firearms firms, products, and markets all changed. New firms that mass-produced patent-protected firearms for civilian markets redefined industry structure. Yet the government and networks formed in the contracting system supplied essential continuity. Through this continuity Americans developed the interchangeable-parts firearms that impressed the world at the Crystal Palace Exhibition in 1851 and British visitors two years later. The same continuity would powerfully support the war effort that was to come.

In 1835 mass-produced firearms met government demand, but traditional gunsmiths met civilian needs. Annual output at Springfield averaged 14,000 muskets and rifles in the 1830s, 11,000 in the 1840s, and 14,000 in the 1850s; Harpers Ferry averaged somewhat less. Repeated private contracts for existing firearms were rare after musket contracts ended in 1840. Among early New England armories only Whitney continued to the Civil War. Many firms entered, including Colt, Winchester, Smith and Wesson, and Remington. Their markets were mostly civilian; Colt's 63,000 revolvers made in 1856 and 1857 were nearly twice its cumulated government sales over the previous two decades. Whereas in 1820 all the largest armorers sold to the government, in 1860 Colt, Sharps Rifle, Smith & Wesson, and other large firms targeted civilian markets.[71]

The new firms made novel, typically patented products, contributing to a transformation from muzzle-loading flintlock muskets or rifles to percussion lock rifles or revolvers using metallic cartridges. The transition began in the 1820s and was still under way during the Civil War. Inventors devised dozens of variations in percussioning, ammunition, ammunition-loading, and repeating mechanisms.[72] Firearm invention grew from 3.7 surveyed patents annually from 1826 through 1845 to 64.8 from 1856 through 1865 (see tables 3.1–4). Firearms were used widely, and patentees were more dispersed than firearms production. New England had two-thirds of industry output but three-eighths of post-1835 patents. Machinists constituted one-quarter of the inventors with known occupations, the lowest share outside clockmaking. Gunsmiths made up one-third of inventors; they and others with mechanical knowledge formed two-thirds of inventors. One-third of inventors learned in firearms networks, with about half of firearms patents; firearms users from many occupations invented.[73] Half of the firearms inventors assigned rights to others, many to firearms firms. Colt, Smith & Wesson, Winchester, and other firms used their own patents. Three-fifths of patentees were positioned to secure usage. The prize was to produce tens of thousands of firearms per year, and by 1860 a few had won it, with the help of vigilant prosecution of infringers.

The armory system shaped even the most civilian-oriented firms. Federal contracts remained important, especially early in a firm's history, and armory practice directed contractors' production processes. Consider Samuel Colt. He patented a six-shot revolver in 1836 and immediately set up a Paterson firm to produce it. Son of a Hartford textile manufacturer, Colt knew of North's and Whitney's accomplishments in firearms and sought to use machinery to mass-produce firearms for military markets. He studied equipment in the Springfield Armory, at factories of contractors Simeon North and Ames Manufacturing, and at the Collins Axe Company. His revolver design needed improvement, and the firm's superintendent, trained in textile mills, could not mass-produce it. In spite of improvements, the firm failed. Colt secured a federal contract for 1,000 pistols in 1847, as the Mexican-American War progressed. Key parts were made in Eli Whitney's factory, superintended by Thomas Warner, a past master armorer at the Springfield Armory. After the contract's completion, Colt negotiated to keep the patterns and newly constructed machinery, with which he equipped his first Hartford factory. Without the revenue, equipment, and learning from this contract, Colt might not have succeeded at all. He hired Elisha Root to superintend the plant. Root had superintended the Collins Axe Company and acquired enough knowledge of mass production metalworking to be offered the master armorer's position at the Springfield Armory, which he turned down. Root hired skilled workers, some from government contractors, built specialized machines, and in 1854 completed a leading plant. Further army and navy contracts contributed to the success. Hence, the most successful firearms producer for civilian markets relied on federal contracts and continuing exposure to armory practice.[74]

As armory practice developed, the benefits bestowed on private producers increased. The Springfield Armory had made great strides toward mechanized production, but it still employed six workers for every machine in 1839. Over the next two decades many gifted mechanics developed mechanization and accuracy. They improved gauging methods, developed milling techniques, overhauled Blanchard's system of stocking machines, and deepened Hall's drop-forging methods. The Armory developed wholly new machinery, including Cyrus Buckland's automatic rifling machines. It learned from contractors, including Connecticut firms that advanced milling machines and the turret lathe. The Armory learned from workers, visitors, communications and publications, and machine tool purchases from leading New England, New York, and Philadelphia firms. It brought barrel-rolling techniques from Britain in 1860, one of the few cases of imported techniques. Springfield effected a dramatic change in technology, one in which, the 1853 British Parliamentary delegation noted, specialized machinery made each part and

then an assembler used "nothing but the turnscrew to put the musket together." The Armory did not achieve mechanized interchangeability; skilled filers were essential to the process. But it came much closer than it had been to this goal.[75]

Armory practice shaped firearms manufacturing more generally. Its contractors were one linkage. Obligations to share knowledge fell as federal contracts declined, but sharing persisted. Private armories including Ames Manufacturing and Robbins & Lawrence learned directly from Springfield, which opened its doors to observers, lent patterns, and taught machinery methods. The movement of prominent armory workers spread techniques. The Springfield machinist Jacob MacFarland and the Harpers Ferry master armorer James Burton both went to Ames. Ames and others sold machines using Springfield designs. Through such mechanisms firearms firms learned from the Armory and its communication network. Private firms were less interested in interchangeability and more concerned about reducing costs and ensuring product quality. But these interests led them in that direction: more precision in production moved their products closer to uniformity and made them less difficul to repair.[76]

The result was a network in which communication centered around public and private armories. Whereas textile networks included textile machinery, firearms networks included machine tools. Traditionally made in-house, firearms firms and others came to sell machine tools within and outside the firearms industry; much of the Connecticut Valley machine tool industry met the needs of Springfield, Robbins and Lawrence, and Colt armories. Such firms and machinists' mobility spread knowledge from the armories. Robbins and Lawrence, which joined Ames Manufacturing in receiving the largest orders from the British Parliamentary Committee, illustrates the operation of the network. Formed in 1844, it purchased machinery from Ames and, with the help of machinists Frederick Howe and Henry Stone, developed mass production techniques to meet a number of government and civilian contracts. It was a leading innovator in machine tools for firearms work and sold milling machines and turret lathes from the early 1850s. After it collapsed, a casualty of poor investments and British contract penalties, Richard Lawrence headed the Sharps Rifle Company, Howe superintended the Newark Machine Company and the Providence Tool Company, and Stone made firearms and sewing machines. Two other machinists improved drop forging at Colt. Likewise, Ames and Colt sold machine tools and trained machinists who spread their methods. Less open than the earlier armory system, production knowledge moved readily, though Root, Howe, and others patented machine tools. By 1860 the network supplied rapidly growing markets for civilian firearms and other products. Shortly afterward, its industrial methods turned to war.[77]

Modes of Continuing Mechanization

The story of ongoing mechanization in early-industrializing sectors was one of path dependence. Innovation continued along paths that had been established before 1835. Institutions that structured the paths formed problem-solving capabilities, networks to communicate knowledge, and incentives to make and spread inventions. Historically, institutions often inhibited change through inertia or outright suppression. Crafts that communicated knowledge frequently resisted change, so that innovation came from the outside. But in ongoing industrialization, institutions created conditions for innovation to occur and spread. Industrial firms had incentives to overcome technical problems, and prior development created conditions and agents of ongoing change. Even if firms sought to protect their fixed investments or avoid the uncertainty of innovating, competition made inertia a risky strategy.[78] Change was irrepressible, as reflected in the altered cast of characters. A few early manufacturers continued to lead after 1835, including Lowell textile firms, Allaire, Hoe, and the Springfield Armory, though many went under. But competitors arose and challenged for the lead. Ongoing industrialization retained and deepened institutions, even at the expense of key organizations.

The diversity of development paths persisted as industrialization continued. Paths varied in agents, location, markets, and innovative processes. Each path involved technological knowledge of practitioners, though some centered more on machinists and others on users. Few people were involved in more than one network. Machinists were central to many paths but less so in clock making and firearms. Each path involved users, but the textile firms, printers, clock makers, woodworkers, and armorers were essentially nonintersecting groups. The location of invention, scale of markets, and technological problems varied as well. Ongoing industrialization occurred in distinct processes with their own dynamics.

Innovation paths changed in several ways. Capital goods firms became central to each path except perhaps clocks and watches, in which firms made many of their own machines, and to a lesser extent firearms. Only exceptionally did textile firms, engine users, or woodworkers make their own production machinery. Because capital goods firms sold to growing numbers of customers and experienced rapid movement of machinists, network flows of knowledge became broader, integrating larger numbers into leading technologies. Much knowledge widened spatially. Many sectors were more integrated internationally; ideas and equipment more readily flowed into the United States after legal barriers were overcome and capital good sales increased. Domestic knowledge flows fostered wider innovation. Textile technologies such as the self-acting mule flowed in,

but ring spinning was indigenous. Engine dynamics were largely domestic. Press technology was international, but after the Napier press was copied, U.S. firms undertook later development largely on their own. Clocks, woodworking, and firearms continued to follow domestic trajectories. Within the country, even as commodities found national markets, innovation remained localized in clocks, printing presses, and firearms; grew more localized in textiles; formed new localizations in watches; yet spread in engines and woodworking.

Patenting grew in importance. The initial development of textiles, printing, and to a lesser degree engines relied on unpatented diffusion; each came to depend fundamentally on patented inventions. Firearms had rested on shared technology, but patented firearms were central after 1835. Some clocks, watches, and machine tools were patented, but much technology was shared. Woodworking was the most continuous, having spread by patent assignments since the appearance of Blanchard's lathe. The development of the new patent system in 1836 and the associated rise of patent agents reinforced the importance of patenting.

Even as networks expanded, so did learning outside networks. Growing book and journal publication, mechanics' associations, industrial exhibitions, and technical education widened knowledge about leading sectors. Off-the-job diffusion was especially important in steam engineering, but even there, practitioners enjoyed major innovational advantages. Other sectors relied more on occupational knowledge. Communities of practice continued to structure their own knowledge, with significant costs of access for outsiders.

Outside innovations overcame critical limits in many early-industrializing sectors. A number of paths had been limited by production capabilities, especially when heavy machining was involved. Textile machinery, engines, and cylinder presses were all limited by inadequate metalworking techniques, as was interchangeability in firearms. The development of technologically convergent metalworking methods overcame many of these limits.[79] European diffusion and indigenous innovation both mattered. Planers, engine lathes, steam hammers, die forging, and other metalworking improvements helped overcome limits to machine construction in many sectors. Printing and coastal textile production relied on developments in engine making. Watchmaking benefited from developments at the Springfield Armory. Armory developments were supported by Root's earlier ax making, Howe's textile training, and outside machine tool improvements. Hoe's press-making and Gay's textile machinery work contributed to their woodworking innovations in saws and planers. One reason innovation persisted was that outside developments overcame internal limits. Paths of development continued by being less autonomous.

CHAPTER FOUR

Contours of Innovation

After touring American factories and shops in 1853, Joseph Whitworth was impressed above all with the pace and generality of U.S. innovation. American development, he wrote, "instead of being, as in former cases, gradual and protracted through ages, is by the universal application of machinery effected with a rapidity that is altogether unprecedented." General metalworking and engine making lagged behind England but were catching up. American textiles had closed much of the gap. Americans led in firearms, woodworking, clock making, and agricultural machinery and used telegraphs and sewing machines most widely. Whitworth also noted innovations in railroads, brass products, cotton gins, pins, nails, locks, rubber, flour milling, stone machines, waterpower, casting, and machine tools.[1] The U.S. economy on the eve of the Civil War differed fundamentally from its Revolutionary War counterpart.

Why was innovation so extensive? Whitworth identified factors operating from above, including widespread education, the press, and the patent system. Diffusion from abroad also contributed. A great many innovations came from below, the products of indigenous problem solvers. But who were the innovators? How did they succeed? Did they learn through networks within industries, or did learning span industries, spreading benefits of some industries to others?

To answer such questions requires knowledge of innovators and inventors from across the economy. Using studies of over a thousand inventors and major innovators, this chapter provides first answers and supplies cases, themes, and direction for the rest of the book. Invention proceeded across a broad front, multiplying inventors over time. Innovators were widespread but concentrated among those who were educated and who acquired technological knowledge on and off the job. They invented where their knowledge was greatest. Because locations varied greatly in knowledge, they also differed in inventiveness. Invention frequently worked, and commercialization fed back to invention by spreading

knowledge and adding inventors. A new method of invention penetrated much of the economy.

The Breadth of Innovation

A look at the 1860 census suggests how different the economy had become. Most of the dozen largest manufacturing industries—together employing nearly three-fifths of all manufacturing workers—had changed fundamentally since independence (table 4.1). The cotton and woolen textile industries had been revolutionized. Clothing and shoes had been reorganized by putting-out systems but retained craft techniques until the sewing and pegging machines of the 1850s appeared. That machinery was the fifth largest industry signaled the breadth of technological change, just as the rise of iron industries manifested an increasingly central material of production. Planers, circular saws, lathes, and mortising machines mechanized much of the lumber, carriage, and furniture industries. Oliver Evans and his followers substantially automated large flour mills. From a modest craft, printing and publishing had become a major industry. The next largest industries utilized the Fourdrinner paper-making machine; metalworking machines to manufacture nails, screws, and hardware; woodworking machines to make windows and shingles; stone-cutting machines; and gas illuminants.

The significance of such innovations should not be exaggerated. They had only begun to diffuse in many sectors. Hand methods were retained in parts of textiles, more in clothing, and even more in shoemaking, in which bottoming machines were only beginning to make inroads. Craftsmen from 1790 would have understood many of the methods to cast iron and make leather. In some industries power-driven machinery predominated, including textiles, lumber, flour, and iron, but mechanical power was just beginning to ascend in furniture, clothing, and leather and was exceptional in shoes and wagon making.[2] Yet clearly innovations had major effects. They had transformed many manufacturing industries and had significant impacts on other parts of the economy. New planters, reapers, mowers, and threshers mechanized much of the agricultural cycle. The steamboat and railroad mechanized transportation. The telegraph revolutionized a small but significant communication medium. Dredging, drilling, and excavating equipment changed construction and mining at the margins.[3]

Hundreds of major innovators contributed to technological changes, thousands of inventors made them practical, and tens of thousands diffused them. A first look at each group depicts the breadth of innovation. Major innovations fell into nine broad types that spanned the economy, each type involving mul-

Table 4.1. Leading Industries and Innovations, 1860

	Workers	Value Added ($1,000s)	Manufacturing Workers, Share (%)	Value Added, Share (%)	Major Technological Innovations
Cotton goods	129,311	65,193	9.9	7.6	spinning and weaving machines
Clothing	126,410	43,704	9.6	5.1	sewing machine
Boots and shoes	123,358	49,501	9.4	5.8	sewing and pegging machines
Lumber	76,827	54,139	5.9	6.3	circular saws and planers
Machinery	54,448	45,096	4.2	5.3	machine tools, steam engines, etc.
Woolen goods	45,367	27,777	3.5	3.3	spinning and weaving machines
Carriages and wagons	39,130	25,368	3.0	3.0	woodworking machines
Iron and steel: basic	38,830	24,175	3.0	2.8	hot blast; Bessemer steel
Furniture	28,733	18,793	2.2	2.2	woodworking machines
Flour and meal	27,682	40,083	2.1	4.7	automated mills
Iron: cast	26,961	21,114	2.1	2.5	incremental foundry improvements
Leather	26,246	25,886	2.0	3.0	incremental tanning improvements
Printing and publishing	25,722	21,014	2.0	2.5	new printing presses
All large industries	769,025	461,842	58.6	54.1	

Source: U.S. Census Office, *Eighth Census of the United States, 1860,* vol. 3: *Manufactures of the United States in 1860* (Washington, D.C.: Government Printing Office, 1865).

Notes: The listed industries each employed at least 25,000 workers and had value added over $20 million.

tiple kinds of knowledge and related networks (table 4.2). Innovations reshaped textiles, clothing, and, nascently, shoemaking. Instrument innovations altered firearms, clocks, scales, locks, and scientific implements. Craft innovations affected masons, potters, jewelers, carpenters, and piano makers. Metalworking innovators developed techniques to form, cast, and machine metals and to make products such as screws and nails. Agricultural innovations varied by operation (planting vs. harvesting vs. milling) and object (grains, cotton, and animal husbandry). Chemical and electrical innovation involved scientific knowledge, and construction innovations entailed civil engineering knowledge. The country advanced in a broad front of techniques, for hundreds of uses, based on a wide variety of knowledge. Patents were distributed just as widely. Agriculture, woodworking, boilers, and stoves had patent shares twice as high as innovator shares, while science-based industries, textiles, steam engines, printing presses, clocks,

Table 4.2. Innovations, Patents, and Exhibits by Type

	Innovators	Innovators, Share by Type (%)	Patents, Share by Type (%)	New York Exhibition Shares (%)
Textiles and apparel	36	12.8	10.9	18.4
Craft-based	26	9.2	13.8	23.8
Metalworking	37	13.1	13.8	11.6
Agriculture	29	10.3	24.6	14.6
Instruments and mechanisms	43	15.2	8.6	11.0
Transportation	37	13.1	8.2	6.2
Chemical and electrical	32	11.3	4.6	6.7
Power	30	10.6	10.7	4.4
Construction	12	4.3	4.9	3.2
Six early industries	103	36.5	18.8	21.3
Other industries	179	63.5	81.2	78.7
1790–1835 share	67	23.8	15.3	—
1836–65 share	215	76.2	84.7	—

Sources: For major innovators, see Dumas Malone, ed., *Dictionary of American Biography* (New York: Scribner, 1937); *National Cyclopaedia of American Biography* (New York: J. T. White, 1898–); *A Biographical Dictionary of American Civil Engineers,* 2 vols. (New York: American Society of Civil Engineers, 1972 and 1991). For typical patentees and all patents, see Edmund Burke, *List of Patents for Inventions and Designs, Issued by the United States, from 1790 to 1847* (Washington, D.C.: J. & G. S. Gideon, 1847); U.S. Patent Office, *Annual Report of the Commissioner of Patents* (Washington, D.C., 1839–65). New York Exhibition data taken from *Official Catalogue of the New York Exhibition of the Industry of All Nations, 1853*, 1st rev. ed. (New York: George P. Putnam, 1853).

Note: Total innovators = 282; total surveyed patents = 1,819; total exhibitions included = 1,988.

and firearms were the reverse. But the basic conclusion is clear: patents and innovations both spread across widely across the economy.

Commercialization cannot be measured so readily, but one indicator is participation at industrial exhibitions. The widest exhibition occurred at the New York world's fair in 1853, the occasion for Whitworth's U.S. tour. Following soon after England's great success at the Crystal Palace Exhibition in 1851, it included over 4,000 entries from around the world. American exhibitors were often manufacturers trying to gain recognition for their products. Exhibits included major technological innovations and incremental product improvements. Americans exhibits spread widely across innovation types. Relative to patents, there were far more exhibits in textiles, apparel, crafts, instruments, and chemicals and fewer in agriculture, power, and transportation. The different distribution reflected the commercial orientation of the fair; it included many consumer products, high in quality but not patentable, including textiles, apparel, daguerrotypes, soap, jewelry, and musical instruments. With this qualification the overall range paralleled those of innovations and patents.[4]

Innovations grew over time. Early-industrializing sectors included only three-eighths of major innovators and only one-fifth of patents or exhibits.[5] Over three-quarters of major innovators concentrated their main efforts after 1835. Even in early-industrializing sectors, 63 percent of innovations occurred after 1835. Early innovators may have contributed to the acceleration by supplying knowledge that benefited later innovators. The growth of patenting was even more striking. From 120 patents per year through 1825, patents increased to 500 annually over the next 20 years, 960 from 1846 through 1855, and 3,770 in the decade through the Civil War, all but 2 percent issued to U.S. residents (fig. 4.1.) One fact illustrates the acceleration: the median patent from 1790 through 1865 was issued in July 1858, nine-tenths of the way through the period. Inventive effort may have grown even faster because few patents were denied before 1836, but 45 percent of applications were rejected over the next three decades.

Nor was the patenting growth a mere reflection of expanding population. Annual patenting increased from 21 per million people in 1816–25 to 29 in 1836–45 and 120 in 1856–65 (fig. 4.2). The gradual increase early in the period accelerated dramatically after 1845. Even early-industrializing sectors received over half of their patents in the 1856–65 decade, and all sectors received three-fifths. The acceleration in patenting paralleled and contributed to the broadening of innovation.

Inventors and Knowledge Acquisition

Just as sampled inventors shed light on innovation in particular sectors, a sample of all inventors illuminates innovation over the whole economy. Inventors will be investigated through a study of patentees. As is well known, patents do not adequately reflect invention. Many patentable inventions were not patented, including the first milling machines and turret lathes. Other inventions (sometimes called "subinventions") did not reach the threshold of patentability yet had economic significance, while many patents had no economic importance. The criteria for accepting patents varied over time. Poorer inventors might not be able to afford the cost of patents, from $60 to $100 if a patent agent was used. Yet most important inventions were patented, and, if interpreted with care, patents provide the best available quantitative representation of inventive activity in an era before research and development.[6]

To construct a data set reflecting the actual distribution of patentees, I began by randomly sampling patentees from annual reports of the commissioner of patents and a summary report of all patents through 1846. The resulting 748 patentees make up the all-inventor sample. All patents from 1790 through 1865

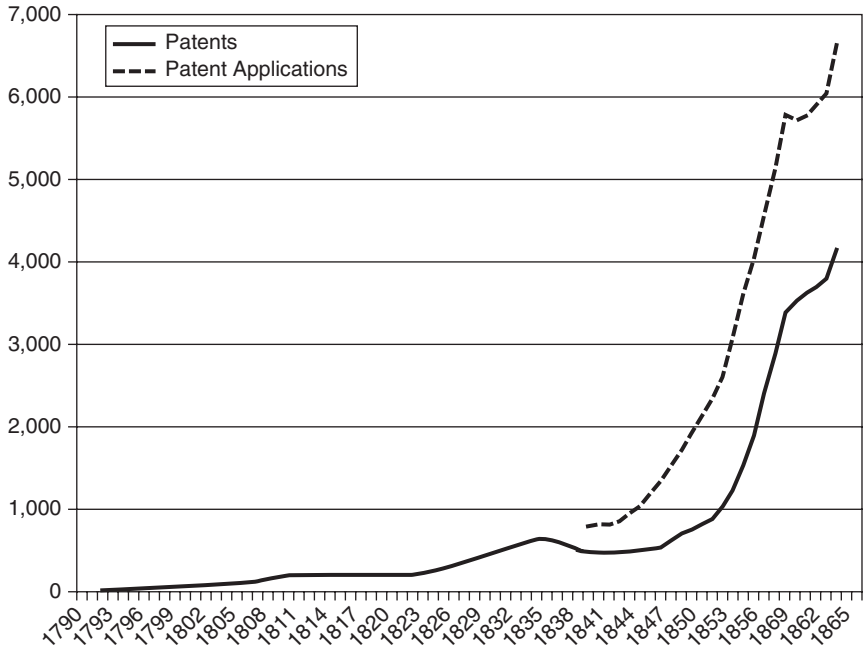

Fig. 4.1. Patents and patent applications (five-year moving averages). *Source:* U.S. Department of Commerce, *Historical Statistics of the United States: Colonial Times to 1970* (Washington, D.C.: Government Printing Office, 1975).

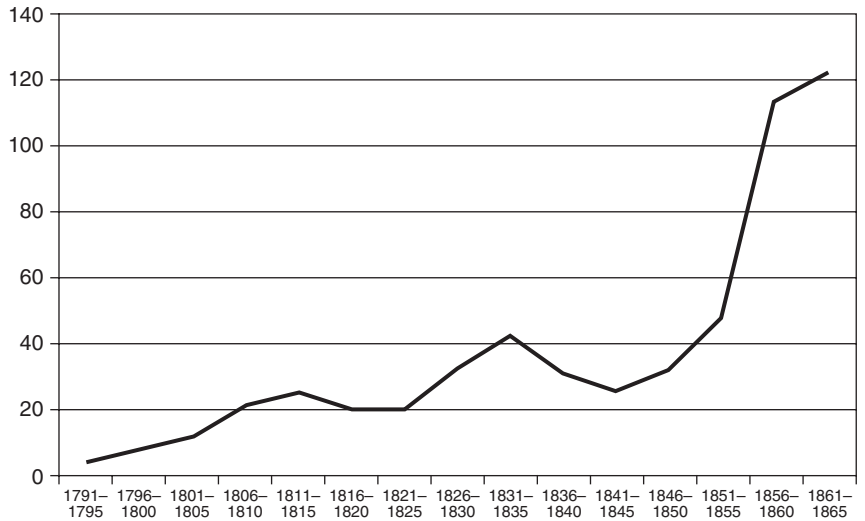

Fig. 4.2. Annual patents per million population.

were ascertained for each inventor, totaling 1,819 patents. Two problems had to be solved before the group mirrored the actual distribution of inventors. First, the sampling procedure is biased in favor of persistent inventors. In a random sample of all inventors, each patentee from 1790 through 1865 would have an equal chance of being selected. The sampling procedure does so within each year but because inventors could have been selected from 20 different sources—the cumulative index of patents through 1846 and annual reports from 1847 through 1865—patentees listed in more sources had more chances to be selected. Hence, an inventor who patented in 10 different years (including the 1790–1846 period as one "year"), had 10 times the likelihood of being selected as an inventor patenting in a single year. I compensated by weighing inventors and their patents by the reciprocal of the number of years in which they invented. In other words, an inventor patenting in two years would be weighted as 0.5 if sampled in only one year and 1.0 if sampled in both. A smaller bias, the oversampling of inventors from 1790 through 1846, was corrected by reducing their weight in proportion to the numbers of patents in these years compared to later years. With the two adjustments the estimated patenting behavior should reflect the whole population of patentees.[7]

When so adjusted, as all data in this book will be, patentees averaged only 1.7 patents from 1790 through 1865 (table 4.3). Seventy percent received a single patent and another 15 percent two patents. Only 5 percent received five or more patents and 1 percent nine or more. Repeat inventors averaged 3.4 patents over the period. By inference about 36,000 inventors patented over the whole period. The great growth of patenting was accomplished largely by a multiplication of inventors, a phenomenon that Kenneth Sokoloff and Zorina Khan have aptly termed the "democratization of invention."[8]

There was little apparent trend toward growing average numbers of patents; the inventor sampled from 1790 through 1835 averaged 1.6 patents, compared to 1.7 for later inventors. But this constancy masked a fundamental change. After the early 1840s inventors patented much more continuously over their lifetimes. Pre-1836 inventors patented only a little after 1835; the 8 percent who did so averaged 1.5 post-1835 patents. A much larger share of later inventors patented after the Civil War. In a study of one-third of the all-inventor sample, 21 percent of 1836–65 inventors also invented after 1865, and they averaged 11.7 patents in the postbellum period. Hence, over their whole inventive careers post-1835 inventors averaged about 4.2 patents—far above the 1.6 for earlier patentees.[9] Patenting growth continued to be generated by expanding numbers of inventors, but repeat invention was rising.

Table 4.3. Typical Inventors by Period, 1790–1865

	1790–1865	1790–1835	1836–1865
Average patents	1.70	1.61	1.72
Average within period	—	1.49	1.71
Share, multiple patents (%)	29.9	25.3	30.8
Avg. patents, repeat inventors	3.36	3.42	3.34
Inventive breadth, repeat inventors	2.09	2.41	2.03
Maximum category, repeat inventors	2.14	1.82	2.20

Sources: Edmund Burke, *List of Patents for Inventions and Designs, Issued by the United States, from 1790 to 1847* (Washington, D.C.: J. & G. S. Gideon, 1847); U.S. Patent Office, *Annual Report of the Commissioner of Patents* (Washington, D.C., 1839–65).

Note: Repeat inventors received more than one patent. Inventive breadth counts the number of patent categories in which an inventor patented, with patents divided into 34 categories. The maximum category is the one in which the patentee received most patents.

Some inventors patented widely. Patentees' inventive breadth can be measured by the number of patent categories in which they received patents. The Patent Office adopted a 22-category classification through the mid-1850s, but for our purposes more refinement is needed. By reclassifying patents into 34 categories, the broad class of metalware can be divided into basic metals, ironworking techniques and products, and machine tools, and "calorifics" can separate out cooking stoves, lamps, and chimneys. Patentees averaged only 1.3 categories, and repeat inventors averaged 2.1, with three-fifths patenting in more than one category. Some patented in complementary categories usable in the same industry, but most patents in distinct categories were not complements. Inventors did specialize to some extent. Repeat inventors received 2.1 patents in their largest category, almost two-thirds of their patents. Such specialization rose modestly over time.

The growth of patents can be interpreted as a response to growing markets and increased incentives to invent. Kenneth Sokoloff argues that through 1846 per capita patenting increased in cycles that mirrored market growth, with growth concentrated in the 1799–1811 and 1823–36 periods. Much the same was true of the later period; per capita patenting grew steadily through the 1850s but fell a bit early in the Civil War.[10] On the other hand, growing patenting also could have reflected the expansion of technological knowledge accompanying growth and industrialization, which affected the costs of invention and its likelihood of success.

Knowledge used to invent was gained on the job and off. Learning through education, technological publications, and wider interactions was an alternative to learning in the factory and through industry networks. For the all-inventor sample only occupations provided systematic information about knowledge

acquisition. City directories listed occupations for 253 inventors. Directories were of little use for inventors in small towns and rural areas, but census manuscripts in 1850 and 1860 (the first years reporting detailed occupational data) included occupations for another 110 inventors. Occupations were known for too few pre-1836 inventors to draw meaningful conclusions. For the post-1835 period occupations were known for 59 percent of inventors, or 54 percent when adjusted to reflect typical inventors.[11]

To highlight the significance of technological knowledge, occupations were divided into five groups: machinists, other manufacturers (including carpenters and others in construction), scientific and inventive occupations (doctors, civil engineers, chemists, patent agents, pattern and model makers, and a few generic inventors), farmers, and those in trade and services. Scientific and inventive occupations often provided services but differed from other service workers in terms of technological knowledge. Machinists include those listed as machinists of any sort, iron founders not specialized in stoves and products other than machines, and a few "engineers" known to have built or run steam engines (excluding civil and mechanical engineers). Iron founders typically used machine tools and were so closely related to machinists that from the 1870 census the two were classified as "Foundries and Machine Shops."

Three occupational groups invented far out of proportion to their numbers. Machinists formed 21 percent of inventors with known occupations, far above the 0.7 percent of the 1860 labor force they made up (table 4.4). Moreover, they were more prolific, averaging 2.9 patents, far more than any other occupational group. Three-fifths of machinist-inventors received more than one patent, and repeat inventors received over four patents. As a result, they received 29 percent of patents among those with known occupations.

Scientific and inventive occupations also were prolific, constituting 10 percent of inventors but well under 1 percent of the total workforce.[12] Like machinists, they had higher shares repeating, and those who repeated took out more additional patents. They and machinists, the two groups with the greatest technological knowledge, together took out two-fifths of all patents. Other manufacturing occupations made up 43 percent of inventors; that they and machinists were over three-fifths of inventors at a time when manufacturing employed about one-eighth of the labor force shows how concentrated invention was in the manufacturing sector. Other occupations invented less often. Trade and service inventors were about 20 percent of the total but repeated less frequently and so received only 13 percent of patents. Farmers and other primary sector workers made up only 7 percent of inventors. Those with the most knowledge of technological

Table 4.4. Patenting by Occupation, 1836–1865

	Machinists	Science and Invention	Other Manufacturers	Trade and Service	Agriculture
Share of inventors (%)	20.7	9.4	43.2	19.3	7.3
Average number of patents	2.93	2.44	1.95	1.39	1.73
Share of patents (%)	29.3	11.1	40.6	12.9	6.1
Repeat inventors share (%)	60.7	48.2	37.0	22.3	48.2
Average number of patents, repeat inventors	4.19	3.99	3.56	2.76	2.51
Inventive breadth, repeat inventors	2.35	2.58	2.05	1.86	1.34
Maximum category, repeat inventors	2.62	2.17	2.38	1.90	2.18

Sources: Edmund Burke, *List of Patents for Inventions and Designs, Issued by the United States, from 1790 to 1847* (Washington, D.C.: J. & G. S. Gideon, 1847); U.S. Patent Office, *Annual Report of the Commissioner of Patents* (Washington, D.C., 1839–65). Occupations were determined from directories for over 60 cities; manuscripts of U.S. censuses of population, 1850 and 1860, accessed at *Ancestry.com*.

problems and solutions—manufacturing, scientific, and inventive occupations—invented most often.[13] They also invented most widely; repeat patentees in each group averaged at least 2.1 categories, led by machinists and scientific inventors. Furthermore, machinists led in patents in their largest category, though other manufacturing inventors were close.[14]

Occupational differences introduce an important supply dimension to invention. Because inventors varied in knowledge, their learning costs differed, reducing invention costs for those with more knowledge and better access to it. Those with wider knowledge could chose strategies more effectively, invent more cheaply, and had greater chances to succeed. Hence, the growth of inventors with technological knowledge had two effects on patenting. First, as technologically knowledgeable occupations grew as a share of all occupations, their share of patents grew. Machinists grew from virtually none in 1790 to about 80,000 in 1860. According to Sokoloff and Khan, machinists and toolmakers increased steadily from 4 percent of urban patents through 1804 to 17 percent from 1836 through 1846, and other metalworkers increased their share from 8 to 21 percent over the same period. The same trends continued through the Civil War.[15] Second, machinists, engineers, and metalworkers transmitted knowledge to other patentees, refined their designs, and made their products, thereby improving inventive prospects for others. Both factors accelerated patenting as a whole.

Within occupations patentees were disproportionately proprietors or supervisors, who had greater technological knowledge and opportunity to appropri-

ate inventive returns within the firm. They also learned from their employees; Edison and others took out patents in their own name to which their workers decisively contributed. City directories identify the position in the firm for about 170 inventors in manufacturing occupations. Almost 50 percent of machinist-inventors and 36 percent of inventors from other manufacturing sectors were principals in their firms (table 4.5). Most were proprietors, but some were superintendents, foremen, or agents. When manufacturing establishments averaged nine employees in 1860, principals invented far of proportion to their numbers. Moreover, principals were more prolific, averaging 70 percent more patents than nonprincipals among machinists and over 40 percent more in other manufacturing occupations. As a consequence, principals received most patents among machinists and close to half of all patents among other manufacturers. They were especially adept at taking out many patents in the same line, averaging almost three patents in their maximum category.[16]

Major innovators were important in themselves, but they also shed light on wider features of invention. Dictionaries of historical biography identify inventors' education, occupation, location, involvement in scientific and technical groups, and contribution to technological and economic development.[17] I examined all innovators active from 1790 through the Civil War who were listed in the *Dictionary of American Biography,* as supplemented by the *National Cyclopedia of American Biography* and *A Biographical Dictionary of American Civil Engineers.* Innovators were mostly identified as inventors by a few words in a biographer's categorization. To get a broader range, I also researched groups of scientists and engineers, who often invented as part of their professional activities. Of the 438 researched, about 370 had technological innovations. For each inventor I identified patents through 1865, a total of almost 2,000 patents. For most purposes I consider the 282 inventors born by 1835 who patented by 1865.[18] This omits 17 percent of innovators who did not patent through 1865. Categorizing inventors by innovation type proved difficult only in a few cases, such as Oliver Evans, known for both automated mills and high-pressure steam engines.

Innovators typically undertook a sequence of inventions lasting many years. Their average of 6.8 patents was four times that of typical inventors (table 4.6). With a median of five patents, they spent considerable time conceiving, perfecting, patenting, and commercializing their inventions. They invented widely yet also specialized, with 4.3 patents in their maximum category, typically the area of their major innovation.[19]

Major innovators had technical training much more frequently than did the whole population. Over half of innovators had mechanical occupations (which

Table 4.5. Patenting and Rank in Firms

	Principals: Machinists	Nonprincipals: Machinists	Principals: Other Manufacturing	Nonprincipals: Other Manufacturing
Share of inventors (%)	47.9	52.1	35.8	64.2
Average number of patents	4.03	2.35	2.77	1.95
Share of patents (%)	61.2	38.8	44.2	55.8
Share, repeat inventors (%)	85.3	45.9	53.3	43.2
Average Number of patents, repeat inventors	4.55	3.94	4.32	3.20
Inventive breadth, repeat inventors	2.27	2.57	2.05	1.95
Maximum category, repeat inventors	2.94	2.28	2.94	2.25

Sources: Edmund Burke, *List of Patents for Inventions and Designs, Issued by the United States, from 1790 to 1847* (Washington, D.C.: J. & G. S. Gideon, 1847); U.S. Patent Office, *Annual Report of the Commissioner of Patents* (Washington, D.C., 1839–65). Status within the firm was determined from directories for over 60 cities; manuscripts of U.S. censuses of population, 1850 and 1860, accessed at *Ancestry.com.*

made mechanisms with moving parts) at the time of their first major patent. Four-fifths were machinists; others made firearms, clocks, locks, and other mechanisms. Machinists averaged the most patents, the greatest inventive breadth, and, except for farmers, the most patents in their maximum category. Another 58 innovators had science-based occupations; half were engineers, and the rest included 8 industrial chemists, 8 mathematics or science professors, 5 in electrical occupations, 3 doctors, and 5 patent agents or examiners. The 12 percent with other manufacturing occupations were led by metalworkers, woodworkers, and textile producers. Agriculture, trade, and service occupations employed a small share of inventors.[20] Occupational change augmented learning. Two-thirds changed occupations as adults, mostly over the course of their inventing. The change expanded innovators' range of knowledge, which may have been reflected in the higher inventive breadth of those who changed occupations.

Many major innovators acquired technological knowledge off the job. One-quarter graduated from college or at least finished much of the curriculum, far surpassing the 1 percent of the college-aged population who attended college. Most attended liberal arts colleges; half went to Ivy League schools, with Harvard, Yale, and Columbia each having seven or eight. Eleven others were trained in applied science at West Point and Rensselaer Polytechnic. Science training was central to the education of both groups. Another 19 percent acquired some scientific and mathematical knowledge in high schools and academies. Overall, 43 percent of major inventors were educated beyond grade school, vastly more than the population at large.[21]

Table 4.6. Characteristics of Major Innovators

	Inventor Share (%)	Average Patents	Inventive Breadth	Maximum Category	Inventor Share, 1790–1835 (%)	Inventor Share, 1836–65 (%)
All	—	6.78	2.73	4.34	—	—
Occupation						
Agriculture	3.6	7.90	2.40	6.20	6.1	2.8
Machinists	44.8	8.31	3.07	5.25	43.9	45.1
Other mechanical	9.6	6.33	2.81	3.93	9.1	9.8
Other manufacturing	12.5	5.51	2.43	3.43	15.2	11.6
Trade and service	8.9	5.60	2.24	3.92	10.6	8.4
Science and invention	20.6	4.83	2.41	3.03	15.2	22.3
Changed occupations	67.9	6.96	2.87	4.23	69.7	67.3
Same occupation	32.1	6.11	2.29	4.54	30.3	32.7
Educational attainment						
College	24.6	5.87	2.54	3.79	25.4	24.4
High school	18.8	7.96	2.78	5.25	11.1	21.1
Grade school and lower	56.6	6.72	2.75	4.29	63.5	54.5
Mechanicians	46.9	7.46	2.98	4.51	40.0	49.0
Nonmechanicians	53.1	6.04	2.45	4.16	60.0	51.0
Prior invention	36.5	8.96	4.02	4.59	34.3	37.2
No prior invention	63.5	5.52	1.98	4.20	65.7	62.8

Sources: Dumas Malone, ed. *Dictionary of American Biography* (New York: Scribner, 1937); *National Cyclopaedia of American Biography* (New York: J. T. White, 1898–); *A Biographical Dictionary of American Civil Engineers,* 2 vols. (New York: American Society of Civil Engineers, 1972 and 1991); Edmund Burke, *List of Patents for Inventions and Designs, Issued by the United States, from 1790 to 1847* (Washington, D.C.: J. & G. S. Gideon, 1847); U.S. Patent Office, Annual Report of the Commissioner of Patents (Washington, D.C., 1839–65).

Note: Cases are omitted when data were insufficient. Educational attainment refers to known education in college or high school; some classified as grade school and lower had high school educations not noted in biographies. Prior invention refers to the presence of patented and unpatented inventions before the first major invention. Innovators are classified in the 1790–1835 period if their major invention was completed before 1836 or, if no invention dominated, if most of their patents were issued prior to that date; others are classified in the 1836–65 period.

Technical reading and scientific societies educated many innovators to become, to use the contemporary term, "mechanicians." Members of this group acquired scientific and mathematical knowledge outside the job, via college training with a focus on science or mathematics, extensive reading, or participation in mechanics' or scientific societies. Almost half of major innovators were mechanicians.[22] Some nonmechanicians also held technological knowledge, including engineers trained on the job and another 92 in mechanical occupations, so that

five-sixths of major innovators acquired wide technological learning on or off the job. At the least the widespread scientific and mathematical knowledge suggests that invention was unlikely to have been the merely "empirical" outcome of unfocused trial and error on the job.

Previous inventions also provided technical knowledge. Lesser inventions were often preludes to greater ones. Thirty-seven percent of major innovators are known to have invented prior to their first major invention. Oliver Evans invented (but did not patent) carding machinery before his flour-milling equipment and steam engine. Thomas Blanchard invented an apple parer, a cloth-shearing machine, and a tack-making machine before coming up with his pattern lathe. Invention was itself a learning process in which the inventor developed capabilities to conceive technical problems, find solutions through experiments and thought, and depict solutions in drawings and models. Such knowledge could aid later invention. For some innovators learning began earlier; their fathers disproportionately concentrated in mechanical occupations, and many of them were themselves inventors.

Many characteristics of innovators were remarkably similar before and after 1835, including the shares with mechanical occupations, college education, and prior invention. Yet later innovators tripled in number, invented more widely, and averaged somewhat more patents (7.2 to 5.4). Average patents within the period (i.e., from 1790 through 1835 for earlier inventors and from 1836 through 1865 for later inventors) grew by about 50 percent. Just as earlier innovators continued patenting after 1835, later inventors patented extensively after the Civil War.[23] The share of scientific occupations grew substantially between the periods due to the growth of engineers from 8 to 17 percent of inventors. While the college-educated share remained constant, the share with only a high school education doubled, passing one-fifth. The number of known mechanicians quadrupled, especially in scientific occupations and mechanical trades. Through formal and informal education and occupational training, later innovators acquired more and better knowledge of applied science. Like their predecessors, later innovators helped build networks of practitioners who developed innovations and extended their range of applicability. The growth of scientific knowledge and mechanicians added to the knowledge acquired in networks but did not alter networks' centrality in innovation.

Invention acquired a spatial structure because inventors' location shaped their interactions, knowledge, and markets. Networks in early-industrializing sectors centered in cities and in the East. Much the same was true for all inventors. Cities were centers of invention. Using urban knowledge and markets, 44 percent of the

all-inventor sample received at least 1 patent when living in cities with over 10,000 residents in 1850, far above the 5 percent of the urban population in 1820 and 12 percent in 1850 (table 4.7). Machinery firms and workers also concentrated in cities, where they used their technological knowledge to invent. Urban patentees patented more, with 2.1 patents compared to 1.2 for others, and took out 54 percent of patents.[24] Urban repeat inventors had greater inventive breadth, reflecting their greater range of learning, but also had more patents in their largest category. Major innovators were even more urban; at some point in their inventive lives, 85 percent lived in cities, led by 63 in New York City, 41 in Philadelphia, and 32 in Boston. Urban innovators cast a wider net, patenting in 2.8 categories, compared to 2.1 for other innovators.

Invention varied markedly by region. The Mid-Atlantic and New England states led patenting through 1835, with much larger shares of inventors than population (see table 4.7). In a remarkable upsurge the West equaled New England in inventor share after 1835, though its population was twice as large. The South lagged, with 12 percent of early inventors and only 5 percent later. Patentee shares after 1835 were much more closely related to machinery worker shares than to population shares.[25] Inventors in the Mid-Atlantic and New England states repeated more often and patented more widely, consistent with the East's greater urbanization and machinery capabilities. Major innovators were even more concentrated in the East.

Major innovators often changed locations to increase opportunities or knowledge. Many left small towns for cities, such as Jacob Perkins's move from Newburyport to Boston, which helped appropriate returns from earlier inventions and led to learning and further invention. Innovators also moved among cities, especially in the Northeast, and between regions or countries, much as Perkins did in coming to Philadelphia and then moving to London. As adults, 52 percent of major innovators moved between U.S. regions or to the United States. European immigrants brought Slater's Arkwright machinery, the scientific instruments Giuseppe Tagliabue acquired in his family's England firm, and the gunpowder methods Eleuthere DuPont learned from Antoine Lavoisier. Just as important, they brought knowledge used to produce and invent in the United States, including Henry Burden's iron-working skills, William Hudson's locomotive training in Robert Stephenson's firm, Thomas Ewbank's sheet metal skills, and John Roebling's bridge design capabilities. Visits furthered learning, such as George Sellers's visit to the Maudslay machine tool plant and Bryan Donkin's paper-making works and Sereno Newton's studies of Napier's printing press. Such mobility created a transnational network of the technically educated, which Anthony F. C. Wallace called "an international fraternity of mechanicians."[26]

Table 4.7. Inventors by Location

	Urban	Nonurban	New England	Mid-Atlantic	South	West
Share of inventors (%)	44.0	29.7	26.3	44.2	6.2	23.4
Average number of patents	2.10	1.18	1.64	1.87	1.62	1.49
Share, multiple patents (%)	41.3	12.7	30.0	35.2	21.2	21.8
Average number of patents, repeat inventors	3.65	2.42	3.12	3.47	3.92	3.23
Inventive breadth, repeat inventors	2.23	1.43	2.06	2.17	1.95	1.89
Max. catg., repeat inventors	2.24	1.99	1.99	2.15	2.47	2.30
Share, urban inventors (%)	—	—	39.4	59.6	33.3	22.6
Share, inventors, 1790–1835 (%)	39.5	28.8	31.7	49.1	12.3	6.9
Share, population, 1820 (%)	5.4	77.7	16.9	32.6	41.7	8.7
Share, inventors, 1836–65 (%)	45.0	29.9	25.1	43.1	4.9	26.9
Share, population, 1850 (%)	11.6	76.6	11.8	28.6	35.6	24.1
Share, machinery workers, 1850 (%)	—	—	32.0	53.6	4.4	9.9

Sources: Edmund Burke, *List of Patents for Inventions and Designs, Issued by the United States, from 1790 to 1847* (Washington, D.C.: J. & G. S. Gideon, 1847); U.S. Patent Office, *Annual Report of the Commissioner of Patents* (Washington, D.C., 1839–65; U.S. Census Office, *Seventh Census of the United States, 1850,* vols. 1 and 3 (Washington, D.C.: Robert Armstrong, 1853); U.S. Department of State, *Census of the United States (1820), Census for 1820* (Washington, D.C.: Gales & Seaton, 1821).

Note: Cities are those with 10,000 population in 1850 for both periods; some did not meet this threshold in 1820.

The geographic mobility of typical inventors is harder to document because so many of them received only a single patent. Census manuscripts do list the birthplaces of 215 inventors around 1850 and 1860. Immigrants formed 18 percent of patentees, exceeding the 13 percent of immigrants in the U.S. population in 1860 (table 4.8). Although some migrated in childhood, many brought skills useful in the new country. Immigrants contributed the most to invention in the Mid-Atlantic States. Twenty-two percent of inventors migrated within the United States to their regions of invention, with net flows strongest to the West. Altogether two-fifths of inventors patented outside their region or country of birth, with about the same share of patents. New England was the most self-contained region, generating five-sixths of its inventors; at the other extreme five-eighths of western inventors were born outside the region. Eastern migrants formed over a third of western inventors but none of southern inventors, helping to account for the inventive rise of the West. Another one-tenth of inventors moved between states within regions.

Table 4.8. Inventors by Region and Birthplace

Place of Birth	New England (%)	Mid-Atlantic (%)	South (%)	West (%)	All (%)
New England	83.7	13.0	0	11.6	30.4
Mid-Atlantic	9.0	58.0	0	23.9	33.9
South	0	1.8	71.8	13.6	7.8
West	0	0.2	12.8	36.7	9.8
Foreign	7.3	27.1	15.4	14.1	18.1
Out-of-region	16.3	42.0	28.2	63.3	9.5

Sources: Edmund Burke, *List of Patents for Inventions and Designs, Issued by the United States, from 1790 to 1847* (Washington, D.C.: J. & G. S. Gideon, 1847); U.S. Patent Office, *Annual Report of the Commissioner of Patents* (Washington, D.C., 1839–65); manuscripts of U.S. censuses of population, 1850 and 1860, accessed at *Ancestry.com.*

Location affected patenting through incentives and learning. Before 1845 patenting grew when and where transportation improved, largely around navigable waterways and the railroad.[27] A similar relationship existed later. In Illinois patenting was concentrated in Chicago and along major rivers and the Chicago and Michigan Canal. Large, integrated markets formed incentives to which inventors responded. Invention also concentrated near technological knowledge in cities and the East. Machinists were most prevalent where patenting was concentrated; they received 32 percent of patents in the Mid-Atlantic States and 34 percent in New England, compared to 16 and 21 percent in the South and West, respectively. As invention in leading areas supported later invention, advantages of superior incentives and learning became self-reinforcing.

The Content and Use of Inventions

Because innovations differed in the knowledge required and the costs of securing the knowledge varied with the inventors' occupation and background, factors supplying knowledge should have shaped the direction of invention. The expected demand for inventions mattered, of course, but inventors would find targets that best used their technical knowledge, and the media through which they acquired such knowledge might also supply knowledge of potential demand and how to tap it. If so, kinds of invention would vary with occupation and background, and the location of invention would vary as well.

Inventors commonly focused efforts on problems learned in occupational networks. Among the all-inventor sample 56 percent of inventors with sufficiently specific occupations had maximum patent categories within their occupations,

and many others had patents linked to their occupations. Two-thirds of stovemakers, blacksmiths, tinners, and brassworkers had their largest patent category in their occupations. Almost half of farmers made agricultural improvements.[28]

Access to knowledge differentiated the inventive objects. Machinists held broadly applicable knowledge, applied the knowledge to many industries, and invented widely. They were important for each early-industrializing sector, constituting from 16 percent of inventors in clocks and watches to 51 percent in steam engineering (table 4.9). Similarly, engineers, patent agents and other applied science and inventive occupations made up from 4 to 20 percent of inventors. On the other hand, occupations with industry-specific knowledge invented within that industry but not much wider. Occupations that used the invention consituted from one-quarter to one-third of inventors in textiles, printing, woodworking, and firearms and three-fifths of those in clocks and watches, as the bold-faced categories down the diagonal indicate. Such inventors were parts of networks that communicated knowledge within their industry.[29] They invented little outside their industry, as indicated by the low off-diagonal shares. Woodworkers invented the most broadly, but their share of inventors outside woodworking was no higher than their share of the workforce. One reason why machinists, engineers, and those in other occupations with widely applicable knowledge invented so much was that they invented widely, whereas occupations with particular knowledge confined invention more to their industry.

Major innovators' occupations clearly shaped their innovations. Machinists and others with mechanical occupations varied from 19 percent among electrical and chemical innovators to 70 percent among metalworking and instrument innovators (table 4.10). Where machinists were low, scientific occupations were high, including most construction, chemical, and electrical innovators. Other manufacturing occupations were most important in craft innovations, in which printers, carpenters, and lamp makers invented, and in textiles and apparel, in which shoemakers and weavers innovated. Farmers were important only in agriculture.[30]

Learning off the job varied significantly among innovations. College-educated innovators formed a majority in chemicals and electricity and in construction, in which they often held engineering and scientific occupations (table 4.11). They were least important in textiles and apparel, craft, and metalworking innovations, but even here, they formed a much larger share of innovators than their workforce share. Francis Lowell, for example, used his Harvard mathematics education to understand British textile machines and develop his own. Innovators who had been educated in high schools and academies were important in every industry, although most had only a grade school education and got their knowledge elsewhere.

Table 4.9. Occupation and Patent Type in Early-Industrializing Sectors, 1836–1865 (Percentage of Inventors with Known Occupations)

Occupation	Textiles	Steam Engineering	Printing Presses	Clocks and Watches	Wood-working	Firearms
Machinists	47.2	50.7	39.5	15.5	44.4	26.7
Science and inventive	4.2	20.1	19.7	5.2	4.9	12.3
Textiles	**30.7**	1.4	0	0	1.2	0
Steam and water	0	**4.1**	0	0	1.2	2.1
Printing	0	0.5	**25.0**	0	0	1.4
Clocks and watches	0.5	1.8	0	**58.6**	1.2	4.1
Woodworking	2.4	5.5	3.9	1.7	**33.3**	3.4
Firearms	0.5	0	0	1.7	0	**30.1**

Sources: Edmund Burke, *List of Patents for Inventions and Designs, Issued by the United States, from 1790 to 1847* (Washington, D.C.: J. & G. S. Gideon, 1847); U.S. Patent Office, *Subject Matter Index of Patents for Inventions Issued by the United States Patent Office from 1790 to 1873, Inclusive* (Washington, D.C.: Government Printing Office, 1874); city directories and census reports, 1850 and 1860, accessed at *Ancestry.com*.

Note: Inventors with known occupations totaled 212 in textiles, 219 in steam engineering, 76 in printing presses, 58 in clocks and watches, 81 in woodworking, and 146 in firearms.

Table 4.10. Major Innovators by Type and Occupation (row percentages)

Type of Innovation	Agriculture	Mechanical	Other Manufacturers	Science and Invention	Trade and Service
Textiles and apparel	2.7	64.9	21.6	0	8.1
Craft-based	3.8	53.8	34.6	0	7.7
Metalworking	0	72.2	13.9	11.1	5.6
Agriculture	25.0	60.7	0	3.6	10.7
Instruments and mechanisms	0	69.8	9.3	16.3	4.7
Transportation	0	40.5	8.1	32.4	18.9
Chemical and electrical	0	18.8	12.5	56.3	12.5
Power	3.3	56.7	6.7	26.7	6.7
Construction	0	33.3	0	66.7	0.
All	3.6	54.4	12.5	20.6	8.9

Sources: Dumas Malone, ed. *Dictionary of American Biography* (New York: Scribner, 1937); *National Cyclopaedia of American Biography* (New York: J. T. White, 1898–); *A Biographical Dictionary of American Civil Engineers,* 2 vols. (New York: American Society of Civil Engineers, 1972 and 1991).

Note: Cells are row percentages; occupations for each row add up to 100 percent. Each major inventor was assigned one major category of invention based on the most important patent. The 34 categories were aggregated into nine groups. Transportation includes navigation, railroad and wagons. Instruments and mechanisms include clocks, locks, scientific apparatus, scales and other measuring apparatus, and firearms. Agriculture includes food processing. Crafts include printing, woodworking, glass making, and lamp making.

Table 4.11. Innovators by Type and Educational Attainment (row percentages)

Type of Innovation	College	High School	Grade School and Lower	Mechanician	Prior Invention
Textiles and apparel	5.9	17.6	76.5	14.7	36.1
Craft-based	8.0	20.0	72.0	11.5	46.2
Metalworking	17.1	25.7	57.1	58.3	54.1
Agriculture	21.4	10.7	67.9	17.9	13.8
Instruments and mechanisms	22.5	25.0	52.5	48.8	23.3
Transportation	24.3	18.9	56.8	54.1	35.1
Chemical and electrical	50.0	21.9	28.1	78.1	40.6
Power	36.7	10.0	53.3	73.3	43.3
Construction	54.5	9.1	36.4	72.7	41.7
All	24.6	18.8	56.6	46.9	36.5

Sources: See table 4.10.

Mechanicians predominated in construction, power, and chemicals and electricity but were little involved in agricultural, craft-based, and textiles and apparel innovations. Many had formal education, but in metalworking a high proportion of mechanicians gained knowledge elsewhere. In every sector innovators learned from earlier patenting; in all but instruments and agriculture, at least one-third of them had invented before their major innovation appeared.

Knowledge-transmitting mechanisms typically clustered near users and producers. The clustering is reflected in the patent specialization index, which is the regional share of patents of a particular type relative to its share of all patents. An index above one indicates specialization in that patent type. In the all-inventor sample construction and crafts were little specialized, reflecting the wide distribution of these activities (table 4.12). Other types were more specialized. New England's share of textile and apparel patents was 92 percent above its share of all patents, led by its domination of textile and leather product patents. The Mid-Atlantic region specialized in metalworking, engines and power, and chemicals and electricity, paralleling its output shares in these sectors. The West specialized in agriculture, and the South (though the numbers were small), concentrated in navigation, wagons, and stoneworking.

Major innovations similarly varied by location. Agricultural innovators were the least urban and were the only group to concentrate in the West and South (table 4.13). Other types concentrated in the East. Regional shares often reflected the location of industries and their capital goods suppliers, such as textile and apparel in New England. In some cases innovation located closer to capital goods firms than to users, including locomotive concentrations in Philadelphia and

Table 4.12. Patent Specialization Indices by Region, 1836–1865

	New England	Mid- Atlantic	South	West
Textiles and apparel	1.92	0.78	1.13	0.44
Craft-based	0.98	0.99	1.70	0.91
Metalworking	1.05	1.22	0.30	0.61
Agriculture	0.62	0.74	1.37	1.89
Instruments and mechanisms	1.32	1.02	0.31	0.74
Transportation	0.87	1.13	2.07	0.69
Chemical and electrical	0.76	1.44	0.37	0.46
Power	0.79	1.24	0.55	0.79
Construction	1.07	1.00	0	1.09

Sources: See table 4.3.

Note: The patent specialization index is the region's share of patents of a particular type divided by its share of all patents. A region specialized on patent types with indices above 1.0.

Paterson, New Jersey. Usage was not enough to generate innovation; the South and to a lesser extent the West used transportation, power, and electricity innovations but did little to improve them. That occupation, education, and location affected the content of innovation points to the importance of factors distributing technological knowledge, particularly networks in industries and cross-industry transmission mechanisms among machinists, engineers, and mechanicians.

Were patents widely or only exceptionally used? Typically, the choice of inventive object and the decision to patent aimed to secure at least some financial returns. Partly through occupational interactions, inventors learned how to appropriate returns by assigning or licensing patent rights or by using patents in their own production or products. Patent assignments present a lower-bound estimate of the value of patents. I examined assignments from 1836, when Patent Office assignment records are first available, through 1864 for 300 inventors in the all-inventor sample. They assigned extensively, recording about 1,200 assignments over the period. About 44 percent of inventors assigned at least one patent, whether to their own company, other family members, attorneys, or others (table 4.14).[31] Three-eighths of inventors assigned patents outside their family and agents; such assignees presumably invested with expectations of a financial return. An unknown number licensed patents. Most occupations assigned; at least two-fifths of inventors in each occupation except farmers assigned patents to others, with machinists assigning a slightly larger share than others. Clearly, assignment to others was not atypical.

Inventors also secured returns by using the technique in their own firms' production processes or products. Among those surveyed for assignments, one-fifth

Table 4.13. Innovators by Type and Location (row percentages)

Type of Innovation	Urban	Mid-Atlantic	New England	South	West
Textiles and apparel	77.8	19.4	77.8	2.8	0
Craft-based	84.6	42.3	38.5	0	19.2
Metalworking	97.3	56.8	37.8	2.7	2.7
Agriculture	62.1	34.5	10.3	17.2	37.9
Instruments and mechanisms	83.7	41.9	48.8	0	9.3
Transportation	97.3	81.1	5.4	5.4	8.1
Chemical and electrical	87.5	71.9	25.0	0.	3.1
Power	83.3	46.7	40.0	3.3	10.0
Construction	100	75.0	16.7	0	8.3
All	85.5	50.7	35.5	3.5	10.3

Sources: See table 4.10.

Table 4.14. Patent Assignment and Potential Usage, 1836–1865

	Number	Share with Assign-ments (%)	Share, Assigned to Others (%)	Share, Potential Usage (%)	Share of Patents Assigned (%)	Avg. Patents, with Potential Usage	Avg. Patents, without Potential Usage
All	300	43.6	38.3	46.4	27.9	2.77	1.49
All with occupations	192	45.6	39.4	50.6	25.8	3.22	1.66
Machinists	59	55.0	45.9	77.2	25.4	4.23	2.05
Science and invention	21	39.6	39.6	35.7	24.8	5.28	1.92
Other manufacturing	69	45.5	40.5	53.6	27.0	2.88	1.32
Trade and service	30	49.8	42.4	39.9	32.8	1.43	1.74
Agriculture	13	15.5	9.0	9.0	7.7	2.74	1.93

Sources: Edmund Burke, *List of Patents for Inventions and Designs, Issued by the United States, from 1790 to 1847* (Washington, D.C.: J. & G. S. Gideon, 1847); U.S. Patent Office, *Subject Matter Index of Patents for Inventions Issued by the United States Patent Office from 1790 to 1873, Inclusive* (Washington, D.C.: Government Printing Office, 1874); U.S. Patent Office, *Annual Report of the Commissioner of Patents* (Washington, D.C., 1839–65). Patent assignment data are from U.S. Patent Office, "Assignment Index Volumes" and "Patent Assignment Digest," in National Archives, College Park, Md.

Note: Percentages are row percentages; e.g., 43.6 percent of all inventors assigned patents.

of inventors with known occupations were principals who could have used their patents in their own firms, led by machinists. Thirty-six percent of principals assigned patents to others, about the same share as all inventors. The remainder concentrated more on using patents in their own firms. Taking the two modes of appropriation together, nearly half of all inventors gained potential patent usage through assignment to others or use in their own firms. Machinists led the way, with over three-quarters having potential usage. Apparently, patent usage was common.

Inventors could gain use for some patents but not others so that the share of patents used would be considerably smaller than the share of inventors securing some use. Assignment data provide lower-bound estimates of the number of patent assigned. In the all-inventor sample about 28 percent of patents were assigned, the large majority of them to others.[32] Those with any assignments assigned half of their patents. Principals also could use unassigned patents in their own firms. Of course, potential usage often went unrealized. Many assignees abandoned their purchases, and principals found that customers rejected their creations. But if early-industrializing innovators were any indication, many who patented did gain usage and were at the core of industry development.

Commercialization was the end of invention, but it was also the beginning. Inventors who secured usage more frequently continued to invent. Income from usage provided funds. Invention was a source of learning about technology and how to invent, patent, and assign. By focusing attention on opportunities or unsolved problems, usage directed further invention. Those with potential usage had almost twice as many patents as those without such usage (see table 4.14). Recognizing that all patentees had at least one invention, the additional 1.8 patents of principals and assignors was 3.6 times as many as other inventors secured. The absolute gap was greatest for machinery, scientific, and inventive occupations. The difference might only imply that more patents increased the chances that one was valuable, but in many cases usage brought learning or financing that supported continued inventing. Moreover, commercialization and attendant networks spread knowledge and invention to others. In the economy as a whole, as in early-industrializing sectors, commercialization led to further invention.

The Way Forward

Several features of the accelerating pace and expanding breadth of innovations are now apparent. Invention grew mostly through the expanding ranks of inventors, though repeat invention increased from the early 1840s. Inventors often

patented in several categories, focusing on but not limited to inventions within their occupations. Inventors concentrated in occupations with widely applicable technological knowledge, especially machinists, engineers, and inventive professions but also other manufacturing occupations. Principals of firms invented far beyond their share of the workforce. About half of all inventors commercialized patents by assignment or in their own firms. Far from being isolated tinkers, inventors commonly were technologically sophisticated, trained in their sphere of invention, and successful.

These features of antebellum invention help illuminate the acceleration and broadening of innovation. Economists' interpretations have focused on the demand for and supply of inventions. Demand could explain expanded invention if market growth increased inventive incentives sufficiently. Patenting broadly paralleled output growth for the whole economy as well as for particular sectors, though the relation was not particularly close. Larger markets help account for inventive location in and around cities, particularly if superior access to information enabled local inventors to gain use more readily, so that urbanization and market integration would lead invention. Market growth would be more firmly linked to inventive incentives if inventors had dependable ways to appropriate returns to inventions; the strengthened patent system after the 1836 Patent Act and the rise of inventive professions arguably had this effect.

Factors that supplied knowledge shaped who invented. Highly inventive occupations were particularly knowledgeable. They enjoyed lower costs of inventing and higher probabilities of success. Machinists were essential in early-industrializing sectors but also received one quarter of the patents of inventors in other sectors. Growing numbers of machinists and engineers could thus increase the pace of invention. So could growing quality of and access to applied science knowledge off the job. Likewise, principals had design knowledge and opportunities to use inventions that their workers did not hold, which helps explain their greater inventiveness. The growth in the number of machinery and manufacturing firms increased the number of principals and perhaps also invention. Employees did assign patents and form their own firms, but they faced greater costs and uncertainly in gaining use. Inventive occupations concentrated in cities and industrial regions, where technological information was accessible more easily and cheaply and where financial backers could meet inventive costs. Such supply factors can explain the spatial distribution of invention and the greater inventive breadth of urban inventors.[33]

A focus on supply and demand factors risks missing a central point: innovation created conditions for its own continuation. Highly inventive occupations

resulted in considerable part from past industrialization and infrastructure development; past innovations hence bred later ones. Innovations that succeeded or pointed the way to success increased incentives to invent and spread technological knowledge, thus augmenting both the demand and the supply of inventions. Positive feedbacks were integral to the process of ongoing innovation.

Inventive feedbacks took several forms. One was internal to innovation paths. Within networks learning concentrated among practitioners in locations to which knowledge had spread. Membership in networks reduced the costs of acquiring knowledge about technology and of potential users, giving members strong reasons to continue patenting along the same lines. The growth of networks was one reason why repeat invention increased. Successful invention, in turn, expanded the number of network practioners. Early industrializers all exhibited network-structured feedbacks, and other sectors did as well. Because industry studies take account of such dynamics, they are more complete and convincing than any study of the whole economy. Differences between networks, manifested in varying occupations and locations, imply that the economy evolved through an expanding set of innovations, each conditioned by broader economic forces yet also following its own path. The diversity of networks among early industrializers would be amplified in broader ranges of innovations.

Another form of feedback generated or reinforced supportive conditions for innovation. Market growth, legal changes, capital accumulation, governmental policy, and civil organizations all contributed to (or at times inhibited) innovation. Market growth and changes in patent laws added to incentives to invent. Educational institutions and the press formed inventive capabilities and widened information flows across the economy. Development from abroad began and continued innovational dynamics. Complementary innovations in market structure, product design, firm organization, sources of supply, and the development of needs often supported technological change. Technological innovation reinforced many of these factors. Productivity growth accelerated capital accumulation and market growth. Innovation increased returns to educational and legal reform and formed a powerful group of advocates. Innovators were central to educational organizations and to the dissemination of knowledge within the United States and abroad. Such feedbacks contributed significantly to ongoing innovation, but they extend well beyond the focus here and are therefore only touched on.

A third form of feedbacks spread knowledge that linked innovation paths. As we have seen, invention in one industry often fostered invention in others. Printing, engines, and textiles had been limited by production capabilities in 1830, and

the diffusion and invention of new machine tools overcame some of the limits. Likewise, inventors patented in many industries, and for many major innovators earlier invention in other fields supported their major innovation. Organizations of mechanicians were central to cross-industry diffusion and innovation. The rise of new networks thus may have depended on the success of established ones, giving rise to a cumulative process for the whole economy. Such cross-industry processes were essential, though unanticipated, sources of ongoing technological change.

The importance of cross-industry feedbacks suggests a strategy to understand innovation across the economy more fully. Because processes relating innovations to each other were fundamental to the acceleration of invention and innovation, cross-industry structures that spread technological knowledge and united technological change must be studied in their own right. Certain industries, occupations, and organizations organized cross-industry knowledge flows. We call such structures "technological centers." Three centers proved particularly important.

Machinists were the most prominent group of inventors operating in many industries, and the development and importance of the machinery sector contributed widely to invention. Their role linking knowledge in one industry to innovation in other industries was important in early-industrializing sectors and perhaps more generally. Engineers and other applied scientists invented widely, especially where machinists did not, but they also created conditions for many to learn. Science shaped technologies in a variety of sectors, and extraeconomic scientific institutions formed and spread technological knowledge. Finally, inventive occupations such as patents agents, draftsmen, and model builders were important inventors in themselves, and, more structurally, their work in relation to another extraeconomic institution, the patent system, shaped the incentive to invent and the diffusion of knowledge. The technological centers each linked innovation throughout the economy. Understanding the birth of ongoing innovation in the United States rests on accounting for their organization, development, and operation.

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CHAPTER FIVE

Machinists as a Technological Center

As the most widely distributed mechanics' journal in the world with the world's largest patent agency, the *Scientific American* understood the centrality of mechanics in inventing, developing, and producing new techniques. An 1869 article in the journal stated: "It is the mechanic who elaborates the idea of the inventor. He it is who clothes it with a practical form, furnishes it with nerves of steel and muscles of iron, and endows it with life and motion . . . So valuable is mechanical skill to the perfection of an invention that it is not surprising that practical mechanics constitute the large proportion of inventors."[1] The article did not identify any dominant means to train mechanics and use their knowledge, and for good reason; no single path led to technological knowledge. Machinists, engineers, mechanicians, and patent agents learned and communicated in different ways. But each group spread knowledge that fostered technological change across industries; as technological centers, each sped up innovation in the economy as a whole.

To constitute a technological center, a group had to meet three conditions. First, it had to possess knowledge relevant to many industries. Without this "technological convergence," to use Nathan Rosenberg's term, spillovers would not exist. Second, it had to be structured to acquire knowledge of technological problems and solutions from many industries and apply the knowledge to other industries. Such a group could bridge networks in separate industries. Finally, its membership had to be large enough to have wide cross-industry effects. Numbers mattered because even if a single inventor originated a technique, many others developed and spread it. Machinists, applied scientists, and inventive professions came to meet these conditions. Together they reshaped wide ranges of industries, overcoming obstacles that had limited earlier innovation.

Compared to other technological centers, machinists most fully combined invention, development, and production. The machinery sector fostered and to

a considerable extent led cross-industry innovation from the 1830s but not much before that time. As the sector grew, its cross-industry effects expanded. The puzzle is how machinists were structured to lead technological change within industries and also to cross over between industries. To solve the puzzle, a number of questions must be addressed. How did machinists learn about techniques in many industries? How did learning and invention within industries relate to learning and invention between them? Multiproduct firms and machinists employed in many industries likely contributed more to cross-industry invention than specialized firms and less mobile workers. How were cross-industry techniques commercialized? Within industries innovating firms used improvements in their own production processes, machinery firms sold some new products, and new firms made others. New firms might have played a larger role in cross-industry invention. Finally, did the machinery sector evolve in ways that fostered cross-industry innovation? A study of the size and structure of the machinery sector, the inventiveness of that sector, and the cross-industry significance of production techniques and product design will help answer these questions.

Structure and Change in the Machinery Sector

From their inception machinists designed and made more or less novel machines in machine-using or machine-making firms by means of widely applicable technological principles and metalworking techniques. In some industries most machinery was purchased by 1835, and machinery purchases increased greatly by 1860. Capital goods firms that employed machinists to design, make, install, and service machinery constituted the machinery industry (fig. 5.1). Machine-using firms also employed machinists to service machines, replace tools, and perhaps purchase machines. The machinists' occupation (shown as the wider circle) linked both kinds of firms. Information flowed within the plant from the shop floor to the machine shop and from here to machinery firms, and machinists' mobility spread it among firms. Because of ties to particular kinds of machinery and machine users, machinists were embedded in particular knowledge-transmitting networks, including textiles, engines, and so forth (the cones in fig. 5.1).

Through training in machine-using and machine-making firms, machinists acquired knowledge particular to an industry and knowledge that applied more generally. The twofold character of machinists' knowledge shaped two cumulative processes central to ongoing technological change in the middle third of the century. On the one hand, using technological knowledge of particular indus-

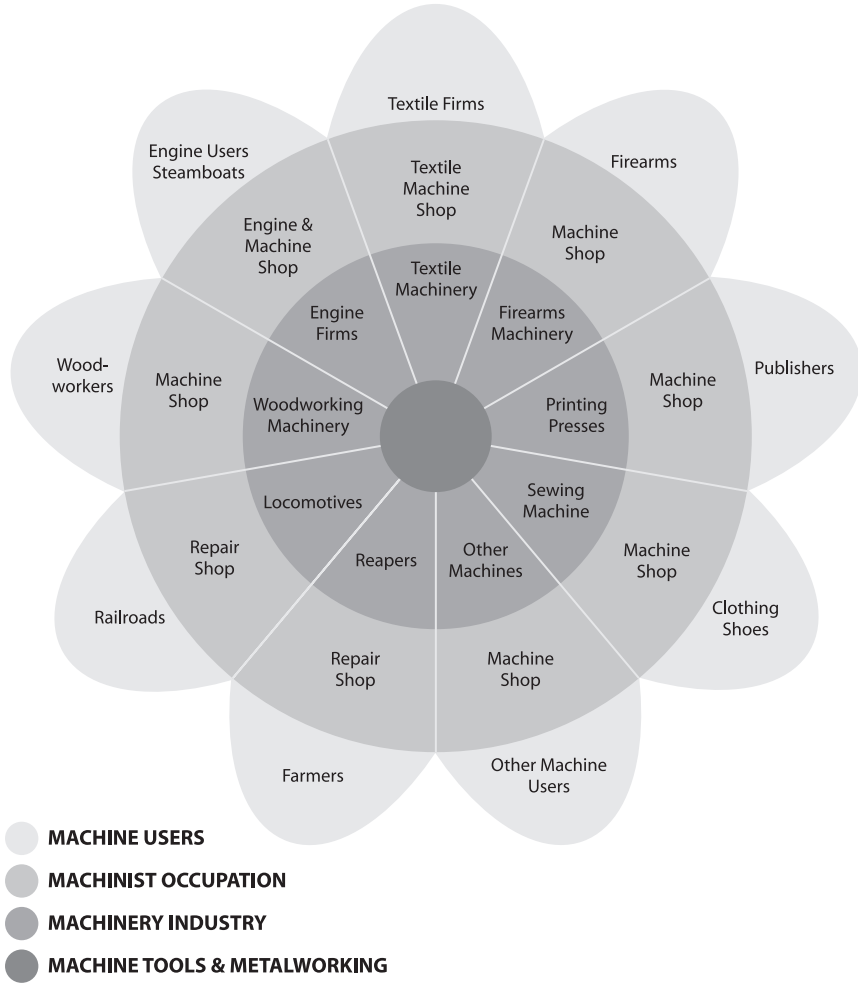

Fig. 5.1. The machinery sector, 1860.

tries gained through industry networks, machinists invented and produced new machines for those industries, resulting in distinct dynamics developing textiles, engines, printing presses, and other machines. From this point of view technology evolved through separate processes each involving machinists.[2]

On the other hand, machinists held widely applicable capabilities in production and machine design, which they used across industries. Steam engines, machine tools, and other capital goods were sold to many industries. Machinery

firms diversified among machinery types, and machinists used knowledge from one industry to invent in others. Universal capabilities were used within the machine tool sector, among different kinds of machinery firms, and by machinists in machine-using firms. Each of those levels connected networks in different industries. Knowledge came to flow within the machinery sector that did not readily flow outside it. That is, textile machinery firms, steam engine firms, and machinists who used their products were linked in ways that weavers, sawyers, and millers were not.

The complex, integrated structure of the 1860 machinery sector was only beginning to take shape in 1830. Earlier processes developing textiles, printing presses, steam engines, clocks, woodworking, and firearms had few linkages. To the extent that cross-industry processes became important, economic development became unified, linking dynamics in particular sectors and realizing potential technological convergences.[3] The puzzle of ongoing technological change, then, had two solutions: networks in individual industries and their capital goods suppliers spread knowledge that advanced technology, and industries generated capabilities that advanced technology in other industries. Such dynamics could drive whole economies.

The evolution of the machinery sector was accompanied by its growth. The machinery industry, defined as including firms making and selling all kinds of machinery but excluding generic foundries, barely existed before 1800. The digests of the 1820 census listed 50 machinery firms employing under 500 machinists (table 5.1). An 1831 report included 120 machinery firms with 2,100 workers.[4] More systematic censuses report 13,000 machinery workers in 1840, 29,000 in 1850, and 54,000 in 1860. By the mid-1830s mechanization was well established in textiles and firearms, and the steam engine was rapidly expanding. From 1840 to 1860 employment in the machinery industry quadrupled. Although manufacturing employment more than doubled in these decades, the industry's share of total manufacturing employment grew by 80 percent. If early data are accurate, average firm size tripled from 1820 to 1850 and then remained largely constant. Over the 1850s the industry grew essentially by adding firms, highlighting the importance of new firm formation.

As an occupation, machinists were more numerous than were employees in machinery firms because many machinists worked in machine-using firms and owners of machinery firms were (and often were recorded as) machinists. In 1850, the first year adequate occupational data were available, over 45,000 machinists worked in the United States, including those listed as machinists, millwrights, and "engineers" (a group, distinct from civil engineers, who mostly ran engines in

Table 5.1. Size and Growth of the Machinery Sector, 1820–1860

	1820	1831	1840	1850	1860	Growth, 1840–1850	Growth, 1850–1860
Machinery employment							
United States	451	2,074	13,001	28,894	54,448	122%	88%
Share, all manufacturing	—	—	2.3%	3.0%	4.2%	—	—
Machinery establishments	50	120	—	1,106	1,912	—	73%
Average employment	9.0	17.3	—	26.1	28.5	—	9%
Machinist, occupation	—	—	—	45,403	79,639	—	75%
Share, all occupations	—	—	—	0.8%	1.0%	—	—

Sources: U.S. Department of State, *Census of the United States (1820), Digest of Accounts of Manufacturing Establishments in the United States and of Their Manufactures* (Washington, D.C.: Gales & Seaton, 1823); [McLane Report] U.S. Congress, House, 1833, *Documents Relative to the Manufactures in the United States;* 22nd Cong., H. Doc. 308; U.S. Census Office, Sixth Census, 1840, *Statistics of the United States of America [at] the Sixth Census;* U.S. Census Office, Seventh Census, 1850, *Abstract of the Statistics of Manufactures;* U.S. Census Office, Eighth Census, 1860, *Manufactures of the United States in 1860*. Occupation data from U.S. Census Office, *Eighth Census of the United States, 1860,* vol. 1: *Population of the United States in 1860* (Washington, D.C.: Government Printing Office, 1864); U.S. Census Office, *Seventh Census of the United States, 1850,* vol. 1 (Washington, D.C.: Robert Armstrong, 1853); Robert A. Margo, "The Labor Force in the Nineteenth Century," in *The Cambridge Economic History of the United States,* ed. Stanley L. Engerman and Robert E. Gallman (Cambridge: Cambridge University Press, 2000), 2:209.

Note: The 1840 census had one listing for the machinery industry; the share of total manufacturing employment is roughly estimated from incomplete published data. The 1850 census grouped together machinists and millwrights, which included textile machinery; I added carding machines, bobbins, and reeds; electrical instruments; and shingle machines. In 1860 I added specialized machinery including agricultural machinery (reapers and mowers, threshers, separators, horsepowers, cotton gins, and stump machines), locomotives, textile machinery, printing presses, sewing machines, machine tools, electrical equipment, turbines, shingle machines, paper machinery, and woodworking machinery. Occupational data refer to males only in 1850 but to all workers in 1860. Because relatively few women were employed in the industry—under 1 percent in 1860, almost all concentrated in auxiliary operations making textile machines—this does not introduce much bias within the machinery sector, but had women's occupations been listed in 1850, the machinist share would have been smaller. I included millwrights, who, like other machinists, worked with gearing and shafting, and most "engineers," who largely were machinists who operated engines in plants, steamboats, and railroads. The 1850 census listed 512 "civil engineers," as distinct from 11,626 "engineers." The 1860 census had one category for "civil and mechanical engineers" which, because of its 27,437 members, must have combined the two 1850 categories. Generic engineers (e.g., those who ran engines) were estimated by assuming that civil engineers made up the same share of all engineers in 1860 as they had in 1850. "Mechanics," who numbered 16,004 in 1850 and 23,492 in 1860, were excluded.

mills, boats, and locomotives). Machinists were half again as numerous as machinery firm employees, and because the firms also employed blacksmiths, painters, and others, machinists outside such firms may have been as numerous as those inside. Machinists grew over the 1850s, numbering almost 80,000 in 1860; because millwrights declined somewhat, "pure" machinists doubled. As machine tools and woodworking

machines joined looms, engines, and printing presses as capital goods, the share of machinists outside machinery firms fell somewhat over time.

Published censuses offer few insights into the structure of the machinery sector. Even in 1860, when some subsectors were listed, over three-fifths of machinery firms were categorized simply as "machinery, steam-engines, etc." Nor do published censuses shed light on the variety of products of individual firms. Census manuscripts help fill the gap. In a study of the 1860 manufacturing manuscripts, I identified 800 machinery firms in 72 leading counties and 17 states. I included all firms selling machinery or machine castings, even if machinery was not the most important product.[5] Entries usually presented detailed breakdowns of the firm's products, and firms were classified by their major type of machine and their extent of specialization. Data for 600 firms from the 1850 manuscripts and 400 firms from the Steam Engine Report of 1838 allow firm structure and persistence to be examined over two critical decades.

Surveyed machinery firms in 1860 were modestly sized. Firms averaged $40,000 in capital, sold products worth $62,000, and employed 48 workers (table 5.2).[6] Workers were virtually all men; only 200 women were listed among 38,000 total. The median firm employed 15 workers, and a quarter of the firms had 5 or fewer workers. The average so exceeded the median because 5 percent of firms employing 200 or more had 45 percent of all workers.

The products spanned much of the economy. Firms are classified by machine specialty if one kind included at least one-third of the firm's total machinery output or figured prominently in the list of products. Clearly, such a standard does not imply specialization in a single machine type. Generic firms made up one-third of the sector's establishments. They included machine shops that made many sorts of machines to custom order and others that did not classify their products, listing simply "machinery" or "machinery and castings." The two oldest machinery groups formed around 1810. Textile machinery firms, concentrated in New England and Pennsylvania, included five firms employing at least 200 workers. Steam engines and boilers, the most common specialty, included large firms in eastern ports and smaller shops throughout the country. Printing press firms, led by R. Hoe, had been around since the 1820s. Firms making machinery to mill grain and sugar, work wood, and make paper originated in the first third of the century, though specialization was more recent.

Other specialties arose after 1835. Agricultural machinery companies concentrated on threshers and "horsepowers" until the reaper revolution of the 1850s; in 1860 the three largest firms all made reapers. Companies regularly selling machine tools developed after 1835. Firms making sewing and leather-working ma-

Table 5.2. Surveyed Machinery Firms, 1860

Type of Machine	Firms, Number	Share of Firms (%)	Capital, Average ($)	Workers, Average	Workers, Median	Workers, High	Average Value of Product ($)
Generic	266	33.3	23,800	32.3	12	800	41,000
Textiles	57	7.1	39,100	61.2	18	725	50,800
Steam engines	155	19.4	48,700	67.2	30	1,000	83,900
Papermaking	7	0.9	34,300	28.3	12	90	50,700
Printing presses	12	1.5	100,700	54.3	25	425	80,800
Milling	13	1.6	41,300	54.3	13	400	87,300
Woodworking	23	2.9	8,700	11.0	7	50	17,200
Agricultural	84	10.5	32,800	31.0	15	200	46,900
Machine tools	28	3.5	40,000	35.1	20	190	48,600
Sewing	57	7.1	24,500	36.4	10	570	98,300
Leather	7	0.9	2,900	5.3	4	10	9,100
Electrical	8	1.0	5,900	6.9	5	16	15,800
Locomotives	17	2.1	212,500	229.9	155	720	261,400
Railroad repair	18	2.3	216,500	191.1	82	990	154,400
Other	48	6.0	21,900	26.6	10	185	34,900
Total	800		39,600	48.4	15	1,000	62,200

Source: U.S. Census Office, Manufacturing Manuscripts from the Eighth Census, 1860 (available in national archives and in state archives in Conn., Del., Md., N.H., N.J., N.Y.).

Note: The few firms that did not report their capital, employment, or value of product were excluded from averages. The survey concentrated on counties where the ratio of machinery employment per capita was at least 50 percent of the national average of 2 machinery and foundry employees per 1,000 people. Surveyed machinery firms were larger than in excluded counties. The survey was also limited to states for which data was available in the national archives and in state archives in the Northeast, which included most New England states, all Mid-Atlantic States, Illinois, Iowa, Kentucky, Michigan, Ohio (for half its counties), Tennessee, and Virginia.

chines formed in the 1850s. Electrical machinery consisted of instruments aimed mostly at telegraphy. The largest machinery establishments made or repaired locomotives. Other specialties included water turbines, steam pumps, and equipment to mint coins, hoist, roll iron, and make bricks, jewelry, clocks, and ice cream. The machinery industry was already widely important; it sold to each of the largest 10 manufacturing industries (including machinery itself) and to farms and transportation and communication firms.

Many firms made a variety of machines. As table 5.3 shows, over 40 percent of firms that provided sufficient detail produced more than one type of machinery (typically two or more of the types listed in table 5.2). Such firms were much larger than others, with average capital and employment almost twice as high. They combined many sorts of machinery. Firms that combined engines with sugar, flour, or sawmills sold a whole line of machinery. Machine tools were of-

Table 5.3. Diversification of Machinery Firms, 1860

Product Characteristics	Firms, Number	Firms, Share (%)	Capital, Average ($)	Workers, Average	Workers, Median	Value of Product, ($)
Two or more types of machinery	216	27.0	67,500	82.6	35	103,300
One type of machinery	304	38.0	37,100	42.7	12	58,000
Unknown	280	35.0	20,900	27.7	12	34,900

Source: U.S. Census Office, Manufacturing Manuscripts from the Eighth Census, 1860 (available in national archives and in state archives in Conn., Del., Md,, N.H., N.J., N.Y.).

ten bundled with machines they made or with woodworking machinery. In 1853 Joseph Whitworth described cases in which "the manufacture of locomotives is combined with that of mill gearing, engine tools, spinning and other machinery," a practice he attributed to the limited size of markets.[7] Diversification varied markedly among types of machinery makers. More than half of the firms specializing in generic machinery, machine tools, printing presses, milling machinery, steam engines, and locomotives made more than one type of machine. Yet only 15 percent of textile machinery firms, 14 percent of sewing machine firms, and 11 percent of agricultural machinery firms were similarly diversified.[8] Diversified firms gained synergies from widely applicable designs, production skills, and facilities. Diversification integrated the industry, making it more than a formal grouping of autonomous, industry-specific firms.

New firms accounted for all the expansion of the machinery industry over the 1850s, as a comparison of census manuscripts of 1850 and 1860 indicates.[9] New firms were most important in rapidly growing sectors. While the number of firms in sectors well established by 1835 grew by 7 percent over the 1850s, firms in sectors that formed after 1835 grew by 103 percent (table 5.4). The clearest example was sewing machines, which grew from no firms in 1850 to 55 of them in 1860. Only three existed in 1850, each a general-purpose machine shop. Agricultural machinery firms grew greatly in number and size, led by reaper firms; none of the major reaper firms in 1860 were listed as such in the 1850 census manuscripts. New firms led the way in machine tools, including the two biggest, Sellers and Bement and Dougherty. Locomotive firms increased their number, though because of large capital requirements, entry largely came from machinery firms established in other branches. In electrical equipment, leather machinery, and other new sectors, firms were virtually all new. The extent of new firm formation was considerably greater than totals suggest because many firms went under. Probably two-thirds of the U.S. machinery firms in 1860 were formed over the previ-

Table 5.4. Transformation of the Machinery Industry, 1850–1860

Type of Machine	Firms, 1850	Average Workers, 1850	Firms, 1860	Average Workers, 1860	Firms, Growth (%)	Average Workers, Growth (%)
Generic	256	23.8	242	28	–5.5	17.6
Textiles	53	55.9	57	61.2	7.5	9.5
Steam engines	91	76.1	123	73.7	35.2	–3.2
Printing presses	7	64	12	54.3	71.4	–15.2
Woodworking	19	10.9	20	11.9	5.3	9.2
Agricultural	38	11.1	64	29.1	68.4	162.2
Machine tools	14	13.2	28	35.1	100.0	165.9
Sewing	0	—	55	37.7	undef.	undef.
Locomotives	9	253.8	16	241.2	77.8	–5.0
Other	49	21.1	79	28.4	61.2	34.6
All	536	29.5	696	44.9	29.9	52.2

Sources: U.S. Census Office, Manufacturing Manuscripts from the Seventh and Eighth censuses, 1850 and 1860 (available in national archives and in state archives in Conn., Del., Md., N.H., N.J., N.Y.).

ous decade.[10] Because most machinery firms listed in the Steam Engine Report of 1838 had failed by 1850, new firms led earlier industry growth as well.

Labor mobility was a principal means to spread knowledge among industries. As noted earlier, two-fifths of Locks and Canals employees between 1838 to 1845 had left the firm by 1845. A minority of them became machinists at textile mills with the same owners, so that the corporate group benefited from the training costs. Most took their skills elsewhere.[11] They often stayed in the textile sector, but especially after 1835 workers spread outside textiles and outside New England. Machinists were mobile between industries, between regions, and into (and out of) the ranks of owners and managers.

Machinists and Invention

The expectation that machinists played a special role in technological change rests on their knowledge of general technological principles and particular applications, their capacity to develop ideas into practical designs, and their ability to translate designs into workable products. Other occupations had knowledge of their own production processes, but machinists were among the few occupations that combined particular knowledge with widely applicable design and production skills. Using such knowledge, machinists developed and produced inventions and innovated often, effectively, and across industry lines.

Inventors often contracted with machinery firms to develop, market, and

manufacture their inventions. Machinists held design and construction capabilities needed to translate elegant ideas into functional machines. Such capabilities were indispensable, as the British engineer Robert Willis highlighted in reflecting on creative machine designs of the sixteenth and seventeenth centuries: "In all that belongs to the mere motion of these contrivances, the greatest possible ingenuity and fertility of invention is displayed. But in all that concerns construction, framing and adaptation of form and dimensions to resistances, strains, and the nature of the work, a total absence of principle and experiences is manifested; so that it is apparent that these machines would act very well in the form of models, but that, if actually set to work, the most of them would knock themselves to pieces in a very short time."[12]

Some firms supported many innovators. When John Howe needed help to perfect and make his pin-making machine, he contracted with R. Hoe and Company. Hoe made a prototype screw-forming machine for Thomas Harvey and then manufactured parts for the first machine to make gimlet-pointed wood screws. Hoe contracted to make steam engines, riveting machines, fan blowers, stone-dressing machines, and other equipment. The company even submitted a proposal to make the blades for McCormick reapers, which McCormick deemed too expensive.[13] Hoe concentrated on contract work throughout the 1830s and 1840s, and many others conducted it later. According to one authority, for those with mechanical problems Boston's Chubbuck Works was "the home of the prophet, the Mecca of America"; if a manufacturer found a new method, "Mr. Chubbuck is the man who is expected to adapt it, and invent means and machinery for its accomplishment."[14]

Machinery firms licensed patents or purchased patent rights to bolster their position within industries and to extend product lines. In a study of one-quarter of machinery principals, one-fifth of machinery firms were assigned patents at the time of patenting, and others acquired rights later. Machinery firms often made and sold others' inventions. One-fifth of 140 firms advertising in business directories marketed products with the names of inventors outside the firm, and the share with such products surely was higher. Some used outside inventions to deepen their product lines, such as the Lynn, Massachusetts, firm that listed 4 shoemaking machines it invented and 12 invented by others. William Sellers marketed prominent boiler injectors and railroad turntables in addition to machines embodying his 21 patents. The variety of products could be great. One Lockport, New York, machine shop advertised the owner's grain-milling machine and 7 inventions by others for grain mills, sawmills, shingle factories, turning and planing wood, and governing steam engines. When superintending the Newark Ma-

chine Company, Frederick Howe acquired wood-planing and horsepower inventions to add to his line of steam engines, machine tools, and firearms machinery. Purchasing patents commonly complemented invention. Over three-quarters of firms that bought patent rights also invented internally. Without machinists' efforts to perfect and produce inventions, others would have gained less usage and, recognizing this, invented less.

Machinists invented extensively. In the all-inventor sample they constituted 21 percent of inventors with 29 percent of patents (see tables 4.4, 4.5, and 4.14). Best positioned to learn and invent, principals made up 48 percent of machinist-inventors with 61 percent of all machinists' patents, some at least partly their employees' work.[15] Principals invented broadly; their 2.1 categories exceeded the 1.7 for other machinists. Machinists' greater inventiveness did not come at the expense of lower-quality patents. Somewhat larger shares of machinists found assignees willing to pay for patent rights, and other machinists used patents in their own firms.[16]

Did machinists invent within their own industries or across industries? They invented in a particularly wide range of industries, which could have resulted from specialized machinists inventing in each sector without linkages to other sectors or from machinists using knowledge from one sector to invent in others. The machinery industry originated out of separate dynamics, and this autonomy might have continued. Such notable inventors as George Crompton, George Corliss, and Richard Hoe concentrated invention within their specialties. Yet machinists also sold machines to many industries and spread knowledge between them, linking industries into a common dynamic.

A study of machinery principals, called the "machinist sample," sheds light on the issue. It also addresses whether invention was a normal part of machinists' work. Principals of machinery firms include partners and occasionally superintendents but not employees of these firms or machinists in other firms. To focus squarely on machinists, I examined only principals who persisted as such for at least four years in the period from 1840 through 1865. This approach required identifying two data points for each person, a criterion that 591 machinists met. Most were identified from firms listed in business directories and city directory advertisements for 52 cities in 23 states, including 15 or more cities in New England, the Middle States, and the West, but only 4 in the South. Census manuscripts and other federal documents help to overcome the urban bias of directories and to identify specialties. Manuscripts for 1850 and 1860 and the 1838 Steam Engine Report identified 331 machinists in the sample; one-third appeared in at least two federal documents. Census manuscripts, business directories, and

advertisements enable classification of principals by the firm's leading type of machine. I identified all patents through 1865 for each principal and also determined assignments for most of them. The counties surveyed had 70 percent of the nation's machinery workers in 1860.[17]

Forty-four percent of principals patented (table 5.5).[18] Invention could be common because it involved few economies of scale; the share of inventors was independent of the size of the firm except for the very smallest. As the share inventing indicates, patenting was a regular but not a required activity of machinery firms. Invention was wider still; S. E. Chubbuck received no patents, yet he and his workers invented a steam engine governor, paper printing machines, rubber machinery, and an elevator.[19] Inventors averaged 4.5 patents, gratifyingly close to the 4.0 patents of machinery principals in the all-inventor sample. Machinist-inventors varied greatly in the extent of patenting. Thirty-three percent took out a single patent, 30 percent had two or three patents, and the 12 percent with 10 or more patents received 46 percent of all patents. Principals invented widely, averaging 2.2 patent types.

Principals who made different kinds of machines diverged in learning, inventive interests, and the extent and content of invention. Those making sewing machines, agricultural machines, locomotives, printing presses, and other specialized machines invented in proportions ranging from 57 to 76 percent. Thirty-four percent of principals of generic and steam engine firms invented, still common enough to depict a planned strategy. Firms targeting machine tools, textiles, and woodworking firms fell in between. Manager-inventors in engine and generic sectors averaged fewer patents, 3.5, compared to the 5.8 taken out by inventors from firms making sewing machines, agricultural machinery, locomotives, and printing presses. As a result, the latter group, one-third as numerous as generic machinists and engine makers, had the same number of patents.

The content of patents paralleled firm specialization. One indicator was the category in which most patents were issued. If it was unrelated to the main business of the firm, then one must doubt that the practice of the firm affected principals' invention. Of inventors with known specializations, 73 percent had their maximum patenting category in their firm's primary product line, and many others had some patents in their product line. In textiles, sewing, agriculture, and other specialized types of machinery, inventors overwhelmingly concentrated on their specialty.

The breadth of invention varied among parts of the machinery industry. Inventors from generic and engine firms invented more broadly but less deeply than others. They averaged 1.8 patents in their largest category—well under the average of 2.9—yet patented in the average number of categories. By contrast sewing

Table 5.5. Invention by Type of Machinery Firm

	Number	Share with Patents (%)	Patents per Inventor	Inventive Breadth	Maximum Category	Maximum in Specialty (%)
Generic	200	35.5	3.7	2.6	1.8	—
Textiles	27	48.1	5.8	2.0	4.5	84.6
Steam engines	156	31.4	3.1	1.8	1.9	59.2
Printing presses	14	57.1	4.9	2.0	3.8	87.5
Woodworking	19	47.4	2.2	1.6	1.6	66.7
Agricultural	30	70.0	6.0	2.0	4.7	95.2
Machine tools	42	52.4	4.7	2.4	2.8	59.1
Sewing	46	76.1	4.7	1.9	3.7	82.9
Locomotives	14	57.1	11.3	3.5	6.9	75.0
Other	43	58.1	5.4	2.4	3.4	72.0
All	591	44.2	4.5	2.2	2.9	73.2

Sources: Edmund Burke, *List of Patents for Inventions and Designs, Issued by the United States, from 1790 to 1847* (Washington, D.C.: J. & G. S. Gideon, 1847); U.S. Patent Office, *Annual Report of the Commissioner of Patents* (Washington, D.C., 1839–65); U.S. Census Office, Manufacturing Manuscripts from the Seventh and Eighth Censuses, 1850 and 1860 (available in national archives and in state archives in Conn., Del., Md., N.H., N.J., and N.Y.); U.S. Treasury Department, "Steam-Engine," 25th Cong., 3rd sess. (serial no. 345), H. Doc. 21, 1839; city and business directories.

Note: In some cases advertisements or contemporary economy-wide surveys allowed classification of firms considered generic according to census returns. Firms listed simply as machinists, when not surveyed in census manuscripts, were classified as generic machinists.

machine, agricultural machinery, locomotive, textile, and printing press inventors averaged 4.3 patents in their maximum category yet invented less broadly than others. More specialized firms learned extensively from single sectors and directed invention accordingly.[20]

Geography differentiated inventive proclivities and breadth. Baltimore, Boston, New York, and Philadelphia were centers of learning with extensive divisions of labor, concentrations of many kinds of machinists, and active mechanics' institutes. Their machinery principals, forming almost two-fifths of those surveyed, patented extensively.[21] The share receiving patents was higher—55 percent compared to 38 percent for others. They averaged 1.6 more patents and received 58 percent of all patents. They invented more widely; the 2.5 categories in which they patented exceeded the 1.9 for other inventive principals. Major-city inventors patented more and more widely in every sector except textiles and agricultural machinery, in which small-town machinists dominated. Major cities were the centers of regional learning, and others within the regions benefited. Nearly half of the principals in the New England and Mid-Atlantic regions patented, compared to 34 percent in the West and 12 percent in the South. Even outside ma-

Table 5.6. Patent Assignment by Firm Specialty

	Assignments (%)	Assigned to Others (%)	Specialty Patents Assigned to Others (%)	Outside Patents Assigned to Others (%)
Generic	69.6	60.9	—	—
Textiles	77.8	55.6	33.3	33.3
Steam engines	44.4	37.0	14.3	46.7
Printing presses	50.0	50.0	0	66.7
Woodworking	66.7	66.7	60.0	25.0
Agricultural	68.8	68.8	60.0	37.5
Machine tools	41.2	35.3	16.7	38.5
Sewing	66.7	52.4	47.1	37.5
Locomotives	57.1	28.6	28.6	0
Other	50.0	37.5	41.7	30.0
All	59.8	50.3	34.7	36.3

Sources: Patent assignment data are from U.S. Patent Office, "Assignment Index Volumes" and "Patent Assignment Digest," in National Archives, College Park, Md.

jor cities, over two-fifths of eastern principals patented, and they invented more broadly than principals in other regions. Machinery principals patented more in settings where they learned more.

Principals did not only purchase patents; half of them assigned at least one patent to others. The puzzle of why principals assigned patents when they could produce their own machinery can be addressed by examining the kind of patents they assigned. Some firms only assigned outside their specialty. One-third of principals who patented in their specialty assigned such patents to others (table 5.6). They concentrated in woodworking, agriculture, and initially sewing machines, sectors in which machines were produced locally and inventors assigned territorial rights.[22] In other cases principals assigned patents before they formed their own firms.

Machinists typically invented for use in their own firm, and invention supported the firm's survival and growth. Among machinery firms in counties surveyed in 1850 and 1860, three-quarters of 1850 firms survived until 1860—a rate far above that for all firms because only firms persisting for four years were examined (table 5.7). Among surviving firms 48 percent had principals that patented, well above the 35 percent among failing firms. Patenting firms survived through the decade more often.[23] Patenting may have aided survival, but it was not necessary or sufficient. Survival and invention were especially strongly related in sectors that industrialized after 1830, including those making locomotives, reapers, sewing machines, and machine tools. In such sectors the 62 percent of surviving

Table 5.7. Firm Survival and Invention, 1850–1860

	All	Early Sectors	Late Sectors
Firms in 1850	280	202	78
Firms surviving until 1860 (%)	75.4	70.8	87.2
Surviving firms with patents (%)	48.3	42.0	61.8
Survival rate, firms with patents (%)	81.0	74.1	93.3
Nonsurviving firms with patents (%)	34.8	35.6	30.0
Survival rate, firms without patents (%)	70.8	68.6	78.8
Firms in 1860	401	260	141
New firms as share of 1860 firms (%)	47.4	45.0	51.8
New firms with patents (%)	48.9	33.3	74.0

Sources: U.S. Census Office, Manufacturing Manuscripts from the Seventh and Eighth censuses, 1850 and 1860 (available in national archives and in state archives in Conn., Del., Md., N.H., N.J., N.Y.); city and business directories.

Note: Only firms in counties surveyed in both the 1850 and 1860 census manuscripts are included.

firms with patents was double the share among nonsurviving firms, and a notably larger share of inventive firms survived.[24]

Invention played a greater role among new firms. A somewhat larger share of firms that formed in the 1850s patented inventions than among earlier firms. New firms with patents averaged 105 employees in 1860, far above the 44 for new firms without patents. Firms surviving from 1850 remained somewhat larger than new firms, pointing to some advantages of an early start. But the gap was modest among new firms that patented. The advantage of inventing was pronounced in recently formed sectors, in which principals invented in almost three-quarters of firms. The largest new reaper, sewing machine, and machine tool firms all invented. In such sectors inventions provided powerful competitive advantages. By sustaining existing firms and helping to form new ones, machinists' invention shaped the growth and composition of the machinery industry.

For many machinists invention was a means to form new firms. Forty-five percent of sampled machinist-inventors received patents before they were listed as principals. Did the machinery sector provide the training through which they invented, or did nonmachinists invent and form machine firms? For nine-tenths of such inventors city directories, population census manuscripts, industrial histories, and biographical dictionaries contained information about their previous occupations. Seventy percent were machinists at the time of their first patent, almost two-thirds as machinery firm proprietors and others as machinists. Another 17 percent of early inventors had closely related occupations as metalworkers, instrument makers, engineers, and inventors. Others had occupations ranging from farmer to

carpenter to merchant. For them invention did lead to machinery occupations, and they then continued to invent as machinists. But the most common path was to be trained as a machinist and then to form machinery firms and invent.

Principals from across the machinery industry had much in common. Each specialty invented frequently inside and outside its field. Each was part of a network in which firms developed and sold machinery that transformed the production of industries using it. Because networks differed, machinists differed in the content of their inventions. For every type of machinery specialty, principals received at least half of their patents in that specialty (table 5.8). Whereas, for example, all machinery firms received about 14 percent of their patents in metalworking, machine tool firms received 53 percent. The share of patents received in the specialty ranged as high as 76 percent for agricultural and textile machinery. Inventive specialization was greater yet because many invented in complementary patent categories, as locomotive firms did when patenting engines and boilers.

But machinists invented far outside their specialties. Even if all metalworking patents were used in their specialty, another 17 to 48 percent of patents had other uses. Some puzzling linkages occurred, such as why locomotive principals received one-tenth of their patents in textiles. Machinists outside the machinery industry also invented broadly. The question is how the machinery sector was structured to provide knowledge and incentives to invent so widely.

Integrating the Machinery Sector: Toward a Machine Tool Industry

The machinery sector could have organized cross-industry invention if machinists making and maintaining machines for one industry spread knowledge that could advance techniques in other industries. Such interactions would have bound together the machinery sector, making it more than an aggregate of independent specialties. The machinery sector itself would take on a dynamic essential for ongoing technological change. Such an internal dynamic was hard to imagine before the 1830s. Machinists were relatively few and were concentrated by industry. Mechanization processes were largely unconnected, undertaken by separate individuals responding to distinct problems in different areas. Machine tools were made in-house or in nearby machine shops or were not used at all. Machine production relied heavily on casting and forging because machining was so difficult. This was an important limit. Hoe could not make cylinder presses for lack of metalworking capabilities. Textile machinists regularly sought out superior machine tools. Zachariah Allen failed to develop his innovative engine

Table 5.8. Patenting by Type of Machinery Firm (percentages of types of patents)

Machine Firm Specialty	Metal-working	Textiles	Steam Engin-eering	Railroad	Printing	Sewing	Agri-culture	Wood-working	Other
Metalworking	**53.4**	1.0	8.7	6.8	3.9	0	3.9	1.9	20.4
Textiles	6.7	**76.0**	5.3	0	0	2.7	2.7	2.7	4.0
Steam engines	14.5	3.9	**50.7**	3.3	2.0	1.3	2.0	0	22.4
Locomotives	2.2	10.0	20.0	**50.0**	0	0	2.2	0	15.6
Printing	5.1	0	5.1	0	**74.4**	0	0	0	15.4
Sewing	3.6	1.8	0.6	0	1.2	**71.1**	1.8	0.6	19.3
Agriculture	7.2	3.2	3.2	0	0	0	**76.0**	1.6	8.8
Woodworking	10.0	5.0	15.0	0	5.0	0	10.0	**50.0**	5.0
Other	6.0	2.2	26.1	0.7	0.7	0.7	0.7	5.2	**57.5**
Generic	18.9	9.1	15.2	2.7	0.4	1.5	5.3	3.8	43.2
All	13.8	9.2	16.5	5.6	3.5	10.9	10.8	2.9	26.8

Sources: Edmund Burke, *List of Patents for Inventions and Designs, Issued by the United States, from 1790 to 1847* (Washington, D.C.: J. & G. S. Gideon, 1847); U.S. Patent Office, *Annual Report of the Commissioner of Patents* (Washington, D.C., 1839–65).

Note: Each row refers to the shares of each type of patent issued to principals of one kind of machinery specialty; the sum of entries in each row is 100. Patent types refer to one of the 34 patent classes except for steam engineering and metalworking. Steam engineering includes steam engines, boilers, and other water and steam devices, along with two steam vehicle patents. Metalworking includes machine tools, metalworking techniques, and generic machine design, such as the regulation of mechanical motion.

because he could not make precise parts. Yet the manifest need was not enough. No machine tool industry existed to meet the need; when Joseph Brown tried to specialize in machine tools in so developed an area as Providence, he found insufficient demand and returned to clock making.[25]

From the 1830s the machinery sector offered greater support to cross-industry innovation. Growing numbers of machinists branched out after 1835. For machinists to spread learning between industries, technologies had to overlap. Technological convergences took two forms. Production convergences included widely applicable metalworking methods, especially the machine tools that came to shape all kinds of machinery but also casting and forging.[26] Design convergences existed if some attributes of machines could be incorporated in other machines or if the principles embodied in some could solve problems in other production processes. In both forms the cost of technological changes in one sector fell because of the utilization of convergent principles from other sectors. Convergent ideas required means to transmit them to other industries. Examples abound of revolutionary techniques that could have shaped other sectors but did not. The sale of capital goods, the mobility of workers, and the formation of new

firms transmitted knowledge within industries; the same factors, supplemented by diversification, also operated between industries.[27]

Consider production convergence first. Technological convergence in machinery production was wide ranging. Machines contained many common parts made in the same way so the capability to make parts for one kind of machinery applied directly to others. In 1833 the order book of Mahlon Betts's Wilmington, Delaware, foundry concentrated on an enormous variety of wheels (described as spur, fly, beveled miter, screw, road, ratchet, crane, saddle, and measuring wheels); pinions, shafts, pulleys, cogs, and other castings. They were used in textiles, ironworking, gunpowder manufacture, paper making, sausage cutters, waterwheels, pumps, milling wheat, shelling corn, and other operations in Wilmington, Philadelphia, and points south. These industries were far wider than those the Providence Iron Foundry had served a dozen years earlier. The very abstractness of the parts suggests their wide applicability, pertaining to what was called "mill machinery" (including gearing and wheels to transmit power to machines) and other universally used machine parts. Likewise, from the firm's origin in 1848, William Sellers's order book listed page after page of pulleys, worm wheels, bevel wheels, gears, collars, hangers, shafts, countershafts, pinions, and clutches, parts used wherever machines were needed. Machine tools had the same universality; Sellers sold them to several railroads, engine makers, railroad wheel manufacturers, sugar refiners, chemical works, pipe makers, and many generic machinists.[28]

Machinists' networks spread metalworking knowledge across industries through worker mobility and machinery markets. William Sellers, Edward Bancroft, Coleman Sellers, and William Bement, who led the country's two largest machine tool firms in 1860, illustrate the cross-industry training of machinists. William Sellers apprenticed at his uncle's Wilmington foundry before moving in the mid-1840s to a Providence steam engine firm, where he worked alongside his partner-to-be, Edward Bancroft, and George Corliss in a firm already using an "English" metal-planer (table 5.9). Bancroft had previously made textile machinery at Matteawan and had worked in Boston and Lowell machine shops. Coleman Sellers made locomotives before joining William Sellers and Company. Bement trained in a New Hampshire cotton machinery firm; became a foreman around 1840 at Amoskeag, which made textile machines, locomotives, and machine tools; moved to Indiana textile machinery and iron firms; and then worked at the Lowell Machine Shop, where he was a contractor and then chief designer.

Sales realized production convergences among widening ranges of machinery. Shafting was so important that in 1850 Bancroft and Sellers advertised their patented "improved shafting, with self-adjusting bearings and double cone cou-

Table 5.9. Cross-Industry Machine Tool Linkages

	Sellers and Bement Training (firms)	Bancroft and Sellers Shafting, 1850 (firms)	Sellers Visitors Register (examples)	New England Firearms Armories (firms)	Brown & Sharpe Universal Milling Customers
Textile machinery	6 (Matteawan, Lowell, Amoskeag)	8 (Lowell, Amoskeag, Matteawan, Whitin)	Mason, Crompton	2 (Crompton)	8 (Mason, Amoskeag)
Steam engines	1 (Fairbanks)	3 (Corliss, Novelty)	Novelty, Root	3 (Porter-Allen)	2 (Corliss, Worth- ington)
Locomotives, railroad equipment	3 (Niles)	2 (Norris, Whitney)	Hinkley, Manchester		4 (Baldwin)
Engraving	1				1 (Gorham)
Machine tools	2		Brown & Sharpe	6 (Pratt & Whitney)	4 (Sellers, Bement)
Generic machinery	1	6 (William Wheeler)		several	6
Railroads		3 (Pennsylvania)	Union Pacific		
Printing presses		1 (Hoe)			1 (Hoe)
Other		11 (U.S. mint)	James Eads		7 (reapers, wood, brass, locks, ammunition)
Firearms (private)			Manhattan Firearms	many	5 (Colt, Spencer, Smith & Wesson)
Firearms (government)			Springfield Armory	many	3 (Springfield)
Tools			Disston (saws)	2 (screws, tools)	4 (Disston, Morse)
Sewing machines			Singer	3 (Wheeler & Wilson, Wilcox & Gibbs)	4 (Singer, Wheeler & Wilson)
Shoemaking					2 (McKay)
Clocks and watches			Seth Thomas	1 (Waltham Watch)	5 (Waltham Watch)

Sources: Sellers, William & Co, "Order Book" and "Visitors Book" (Hagley Library, Wilmington, Del.); Domenic Vitiello, "Engineering the Metropolis: The Sellers Family and Industrial Philadelphia" (Ph.D. diss., Univ. of Pennsylvania, 2004), chap. 3; Brown & Sharpe, *A Brown and Sharpe Catalogue Collection* (Mendham, N.J.: Astragal, 1997), 20–23; Joseph W. Roe, *English and American Tool Builders,* 247–54; David R. Meyer, *Networked Machinists: High-Technology Industries in Antebellum America* (Baltimore: Johns Hopkins Univ. Press, 2006), chap. 5; Hounshell, *From the American System to Mass Production,* 68–82; *Dictionary of American Biography*; *Mechanical Engineers in America Born prior to 1861: A Biographical Dictionary* (New York: American Society of Mechanical Engineers, 1980).

Note: Numbers refer to numbers of firms; names to examples of firms or uses. Foreign firms are omitted.

plings, to admit of easy attachment." They sent samples to 34 prominent machine shops making textile machinery, steam engines, machine tools, locomotives, and printing presses across the East.[29] Visits to factories combined mobility and sales. Sellers kept a visitor's book for four years beginning in November 1861, which over 600 visitors signed from 28 different states and territories and several foreign countries. The list included owners and managers of leading firms in a dozen industries, including Brown and Sharpe in machine tools, William Mason, George Crompton, Holmes Hinkley, Singer Sewing Machine, the Seth Thomas Clock Company, the Novelty Iron Works, and, in firearms, Colt, Smith and Wesson, the Springfield Armory, and the Ordnance Department.

Similar channels diffused firearms techniques. Workers at the Springfield Armory, Robbins and Lawrence, and Colt spread metalworking capabilities to government and private armories and firms making textile machines, clocks, engines, sewing machines, screws, tools, and machine tools. Armories, Ames Manufacturing and other firearms suppliers, and machine tool firms came to sell machine tools that had originally been invented to make firearms. The universal milling machine, a fundamental machine tool invented by Joseph Brown in 1862 to make firearms and sewing machines, had been purchased by 66 firms from over 20 industries by 1867.[30]

The cross-industry spread of machine tools accelerated in the 1840s. The need was clear. Machines could not function precisely, durably, or rapidly without techniques to cut round and plane surfaces accurately. U.S. machine shops could not form either shape accurately in 1825, but by 1860 the engine lathe and the metal-planer performed these tasks in leading shops. Henry Maudslay in England and David Wilkinson in Providence invented the engine lathe before 1800. Diffusion took a quarter-century to reach major shops. Neither inventor sold the lathe. Only one firm purchased Wilkinson's patent rights; he sold some castings and made machines for his own use. The mobility of his workers was more important. Diffusion took a long time even within New England textile machinery production, but when one New England calico printer bought English slide lathes in 1826, his firm protested that it already had a dozen. In an early cross-industry usage the Springfield Armory purchased Wilkinson's lathe castings and adapted the lathe to barrel turning. There is no evidence of its use to make engines or presses.[31] The Middle States acquired the industrial lathe in the mid-1820s, after a Philadelphia machinist bought a Maudslay slide rest from a British worker in 1822 or 1823. The *Journal of the Franklin Institute* immediately perceived its importance: "Where perfect accuracy is required, in turning cylinders, cones or flat surfaces, the slide rest is an appendage to a lathe, which is almost indispensable."

Philadelphia mechanics improved it in the mid-1820s. Matthias Baldwin and others sold it to make printing presses, steamboats, ships, and steam engines around Philadelphia.[32] Others spread it to Pittsburgh, New York, and elsewhere, though it failed to diffuse across much of the country.[33]

The planer spread later but more quickly due to the expansion of potential users and the sale of capital goods. Planers diffused from England, where they reached practical form by 1817 and were widely available by the 1830s. The planer was a major innovation; its origin, according to William Sellers, marked "an era in the life of the machinist, as great, perhaps, as that of the slide rest."[34] American firms are reported to have used metal-planers of some form in 1830, but the major machines came from abroad. Locks and Canals imported a Whitworth planer at about the same time that it began to sell machine tools. In 1838 it sold a metal-planer to Edward Bancroft's steam engine firm in Providence, together "with more tools than we received with our English machines." New York and Philadelphia steam engine and foundry firms used British planers from the same time. Hoe negotiated for planers from Bancroft's firm from 1841 through 1845, bought planers from the Novelty Works, purchased English machine tools and measuring devices from Joseph Whitworth, and returned to U.S. producers from 1850, when its census return reported 11 planing machines and 43 lathes. Bancroft also sold a planer to William Sellers, his future partner, and in 1848 Sellers first sold planers. A decade after they were first imported, planers were used widely—including textile machinery, steam engines, printing presses, generic machinery, and machine tools—but not deeply. Use deepened over the 1850s as others made and invented planers, including William Bement, using knowledge acquired at Lowell.[35]

Lathes and planers were the most widely reported machine tools in 1850 and 1860, but machine tools emanating from the firearms industry also spread. Milling machines were used in textiles, sewing machines, watches, and other industries. The universal milling machine sold widely. Turret lathes, often used to make screws, diffused to many industries. By 1867 Brown and Sharpe sold turret lathes to 4 armories, 5 sewing machine firms, 6 locomotive firms, 3 steam engine firms, 3 textile mills, and 12 firms making machine tools, woodworking machines, other machines, clocks, watches, tools, and brasswork.[36]

Domestic innovation was essential to machine tool development. Such fundamental changes as the first milling machines and turret lathes were not patented, but about 200 machine tools received patents through 1865. Patents rose from a constant decadal average of seven from 1806 through 1845 to 62 in the following decade and 107 from 1856 through 1865. Machinists dominated invention, constituting two-thirds of the post-1835 inventors with known occupations

and receiving four-fifths of the machine tool patents (table 5.10). Most other inventors came from related occupations, including engineers, carpenters, and manufacturers of firearms, clocks, and metal products. Only machinists persisted in patenting machine tools, and they integrated patenting in metalworking, mechanical motion, and steam engineering. Other inventors concentrated more on machine-made firearms and wood products.

Machine tools overcame problems in many industries. Screws of all types, from the precision lead screws of machine tools to mass-produced wood screws, were a common aim, engaging Providence inventors from David Wilkinson through mechanics of the American Screw Company to Joseph Brown. Milling machines and turret lathes produced long runs of homogeneous products. Some targeted the very small, including watch parts; light machine tools also mass-produced firearms and sewing machines. Sellers and Bement concentrated more on making massive marine engines and locomotives. As sales widened, many inventors aimed at generic machine movements rather than particular industries. Reflecting the general importance of machine tool innovation, machinery principals making each major type of machinery also received metalworking patents (table 5.8).

New machine tools solved widely applicable problems. Accuracy in machine fabrication was needed for interchangeability but more generally to make durable, functional products. William Sellers had this goal, as indicated by his concern for "truth": three early patents aimed to prevent a screw shaft from "bring strained out of true," to make shafts or rings "perfectly true when finished," and to make parallel lathe spindle axes by ensuring the "truth of two surfaces of the bed with corresponding surfaces of the heads."[37] Inventors sought to mechanize hand operations. The planer reduced the need for the hand chisel, and the engine lathe for the file. Joseph Brown's universal milling machine made twist drills and much else. When firearms, screws, clocks, locks, and other goods were produced in the tens of thousands, inventors aimed at automation; according to his 1846 patent, Thomas Harvey's screw-making machine used "no other human labor than is necessary to keep the mechanism in order" and to feed material.[38] Turret lathes, milling machines, and forging equipment were central to these efforts.

Machine tool inventions gained use through self-usage, machine sale, or patent assignment. Some inventors targeted the firm's own production process, such as Frederick Howe's turret lathe or Elisha Root's machine tools used to make firearms or the gear cutter George Corliss used to make flywheels for his engines. Controlling the gear cutter was so important to Corliss that he refused to sell one, offering to sell gears instead.[39] Inventions to mass-produce firearms and clocks often were

Table 5.10. Machine Tool Inventors, 1836–1865

	All	Machinists	Science and Invention	Other Manufacturing
Inventors	108	54	8	18
Occupational shares (%)	—	67.5	10.0	22.5
Machine tool patents	1.61	2.09	1.25	1.00
All patents	4.18	4.98	4.25	5.72
Assignments				
Inventors studied	43	31	3	9
Assignment to others (%)	58.1	64.5	33.3	44.4
Machine tools to others (%)	39.5	45.2	33.3	22.2
Machine tool usage (%)	74.4	87.1	33.3	44.4

Sources: Edmund Burke, *List of Patents for Inventions and Designs, Issued by the United States, from 1790 to 1847* (Washington, D.C.: J. & G. S. Gideon, 1847); U.S. Patent Office, *Subject Matter Index of Patents for Inventions Issued by the United States Patent Office from 1790 to 1873, Inclusive* (Washington, D.C.: Government Printing Office, 1874); U.S. Patent Office, *Annual Report of the Commissioner of Patents* (Washington, D.C., 1839–65). Patent assignment data are from U.S. Patent Office, "Assignment Index Volumes" and "Patent Assignment Digest," in National Archives, College Park, Md.

used within the plant, and worker movement commonly spread the techniques. Joseph Brown both used and sold his milling machines and turret lathes.

Many secured usage through sales of capital goods. Three-fifths of machinists who invented machine tools were principals, usually in machinery firms in which they could sell their inventions. Some firms regularly sold machine tools from the late 1830s, including Locks and Canals and Ames Manufacturing. Ames's biggest customer, the visiting British Committee on the Machinery of the United States, bought gunstocking machines and gauges in 1854 valued at $47,000 for use in British armories. The committee spent $46,000 for 140 Robbins and Lawrence machines, almost half for milling locks, and then ordered a barrel-making plant from the firm. Firms only began to specialize in machine tools from the late 1840s. The 1850 census manuscripts list 26 firms that sold at least some machine tools, though often not the firm's primary product, including firms combining machine tools with wood lathes or engines. In 1860, 41 surveyed firms sold machine tools, averaging 32 workers. William Sellers and Company, probably the largest machine tool firm in 1860, sold various sizes and designs of lathes and planing machines from 1848; by 1860 its machine tool sales of $80,000 exceeded shafting and gearing sales of $75,000 and railroad turntable sales of $50,000.[40] Just as machinery firms often split off from factories, so too machine tool firms often split from firms making or using machinery, following a pattern Steven Klepper and Sally Sleeper called "entry by spinoff."[41] After having worked at the Colt Armory, Pratt and Whitney spun off from a milling machine manufacturer.

A city directory ad for Crossley and Allen, a Wilmingon machine tool firm, noted that both partners had headed departments in William Sellers's firm, adding that "this fact is merely mentioned to show that this firm have had the very best kind of experience [*sic*]."[42] It was clearly something Crossley and Allen wanted prospective buyers to know.

Finally, two-fifths of inventors assigned machine tool patents to others, including all the major screw-cutting inventors. Thomas Sloan assigned a dozen patents to the Eagle Screw Company and listed "experimenting" as his product in 1850, with an output of 17 screw machines. Yet major machine tool firms virtually never assigned patents to others, including Brown and Sharpe, Bement, and Pratt and Whitney; Sellers assigned one patent for "ventilating hats." They sold machines embodying their inventions, not the inventions themselves. Between the three sources of usage, 87 percent of machinists were positioned to gain use for their machine tool patents, along with 44 percent of inventors from other manufacturing occupations.

New machine tools did much to spread machinery. Generic lathes and planers went far to overcome metalworking deficiencies that had constrained leading firms making printing presses, textile machinery, engines, locomotives, and other complex machines. Turret lathes and drop-forging methods advanced quantity production. The universal milling machine would become the premier toolroom machine. By solving problems in many industries, new machine tools integrated technological change across the machinery sector.[43] The birth of a machine tool industry and growing cross-industry mobility of machinists accelerated the diffusion and invention of metalworking methods. The complementarily of machining techniques played an important role in the acceleration. Industrial lathes helped build accurate equipment only if the lathes themselves were accurately constructed, and without the planer, this was difficult and expensive to accomplish. Flat lathe beds, required to achieve "truth" in machinery turning, could not readily be made until the 1840s. Accurate measuring devices, such as the vernier caliper Brown and Sharpe marketed from the 1850s, also were required. As machine tool usage grew, diffusion mechanisms and invention also rose. As a result, whereas it had taken 50 years for the slide lathe to diffuse, it took only 5 years for Joseph Brown's universal miller to become widely used.[44]

Augmenting the Machinery Sector: Design Convergence

Machinists were positioned to apply principles of machine design to a variety of industries. Their jobs provided knowledge of principles with varying ranges

of applicability. Principles of gearing, changing reciprocating to rotary motion, and forming flat, round, and irregular surfaces of metal or wood were virtually universal. Steam engineering principles applied to valve gear, steam pumps, and locomotives. Weaving principles were more specific but spilled over into other thread-manipulating industries. Most broadly, many machinists understood the design process of visualization, geometric and at times algebraic and trigonometric conceptualization, and representation in drawings and models. Most drawings lacked precision and scale but effectively communicated mechanical knowledge. Mechanics trained in drawing were in high demand for their ability to adapt designs and develop new ones, and Sellers and other leading firms formed drafting departments.[45]

Machinists learned about inventive opportunities through observing machines, diversifying their firms, or moving between firms. Such modes were often combined in paths full of unintended consequences, as Isaac Singer's experience illustrates. Singer was an itinerant machinist and an aspiring actor who worked for short periods in machine shops in Maryland, New York, Pennsylvania, and the Midwest, including Hoe's press shop. He also invented, including a rock-drilling machine patented in 1839 and a type-forming machine in 1849. He sold partial patent rights to both inventions. To build a working type carver, Singer moved to New York and secured shop space, assistance, and financial support from A. B. Taylor, a prominent New York press maker who also had worked for Hoe. When Taylor's factory was destroyed by an engine explosion, Singer found another partner and moved to Boston. The shop in which he attempted to sell the carver also exhibited an early, defective sewing machine; Singer's invention was designed to solve the problem that plagued the failing machine. He then pursued the sewing machine market in earnest, forming a company and following up his initial sewing machine patent with 19 more. His generic machine-building skills were insufficient to mass-produce the machine, so he sought out leading techniques. Although hardly leaders in mass production, firm members visited the Sellers factory and purchased Brown and Sharpe universal millers and turret lathes. The universal millers made, as Singer's superintendent put it, "every conceivable shape and form of cutter with perfect ease and facility. We should consider ourselves behind the age without them."[46] Being with the age was of more than aesthetic import.

Singer illustrated how the machinery sector created conditions for wide-ranging invention. Experience as a machinist and an inventor provided him with mechanical knowledge that applied to mechanisms as different as rock drilling, type carving, and sewing. He tapped into machinist networks for financing and

technical support for his early inventions. Renting shop space through similar networks turned his attention to sewing. Like others, Singer formed a new firm to make and sell his invention. Machinist training and machine tool purchases aided his production. His firm financed later inventions. It did not diversify out of sewing machines but did make new sewing machines for shoemaking. Singer's inventions—20 sewing machine patents, a rock driller, a type carver, and, after his sewing machine successes, a carriage—point to the complexity of historical processes that spread universal principles among various uses.

How common was Singer's experience? Did machinists use knowledge acquired in one segment of the occupation to advance technology in others? To answer the question fully would require showing that machinists invented widely, that their cross-industry invention derived from occupational learning, and that they utilized machinery experience to commercialize inventions. Such an answer involves extensive detail for many machinists, which biographical dictionaries only begin to supply.[47] But the machinist sample sheds light on each part of the answer.

Machinery principals invented broadly. Over three-fifths of inventive principals patented outside their specialty, and three-eighths of their patents fell outside the specialty. Even a small share could be decisive; Singer received seven-eighths of his patents for sewing machines, but it was his type-carving machine that led him to sewing. George Corliss was quite similar; his efforts to market a sewing machine patent led him to Providence, where a steam engine firm hired him. As the all-inventor sample shows, machinists invented particularly widely; two-fifths patented in more than one category, twice the share of other occupations.

Cross-category invention involved complements and convergences. Complementary innovations often developed in the same network. A practical steam engine involved an engine design, boilers, means to transmit power to equipment, and methods to shape and punch machine parts. Improvements in each would involve five patent categories. Corliss received patents in each, with five engine patents, five boilers, a gear-cutting machine, and machines to forge, roll, and punch metal. Complementary techniques were common, such as furniture inventions linked to woodworking or lamp inventions tied to brassworking. Complements made up 13 percent of patents for principals with known specialties, concentrating in metalworking and steam engineering. Wide inventive breadth would overstate cross-industry invention if such invention was used in the same industry. A quarter of all patents fell outside specialties and complements.

Many inventions for different sectors involved convergent designs. Gearing, cams, and motion-changing methods were universal. Thomas Harvey invented

a printing press using toggle joints, which he then employed on his screw-making machine. Elias Howe's sewing machine was an outgrowth of experience as a Lowell textile machinist, which provided knowledge of thread-manipulating mechanisms.[48] Inventions often shared only quite general principles of machine design. The inventor's experience linked the techniques, such as minor inventions that brought Singer and Corliss to major ones, or the steam engine work that impressed on Sellers the need for "truth" in making machines. Many inventors, including 33 machinery principals, began with patents outside what would become their main inventive category. Among major innovators 44 percent of machinists invented in other areas prior to their major innovation, the highest share of any occupational group. Textiles began the inventive careers of the machine tool inventor Frederick Howe and the screw-making inventor Thomas Sloan. Earlier inventions provided knowledge used in later invention; through such means one mechanized industry could support the development of another. Exposure to a broader range of industries stimulated wider invention, which is one reason for the greater inventive breadth of diversified machinery principals compared to specialized ones or of urban compared to rural machinists.

If machinists used convergent technology in inventing, they would concentrate their invention on machinery, for which design convergences were greatest. A comparison of patenting by machinery principals, machinists in the all-inventor sample, and others in that sample supplies useful evidence. Machinists were most important in developing machines and their production methods. About 16 percent of patents of machinists in the all-inventor sample improved processes and mechanisms of metalworking and machine design, four times the share of other inventors (table 5.11). Machinery principals had the same focus. Principals and other machinists disproportionately concentrated on steam engines, boilers, locomotives, and related steam engineering equipment. Within these categories they focused more on engines and boilers and less on steam heating and plumbing equipment. Machinists also centered much more on textile and sewing machinery. Among agricultural improvements they focused on harvesters and mowers. Machinists had a modestly higher share of woodworking patents and, among such patents, a higher proportion of generic wood lathes, planers, saws, and mortising machines. Machinery principals received 27 percent of their patents in other categories, compared to 65 percent for nonmachinists, and in such categories machinists focused more on machines, including those to peg shoes, make paper, and transmit electricity. Machinists patented where mechanical principles dominated.

Complementary and convergent inventions gained cross-industry significance

through multi-industry markets, diversification, assignment, and new firm formation. Machines had cross-industry effects when they were used in many industries, such as that archetypal general-purpose technology, the steam engine. By the Civil War the Corliss engine was used in textiles, iron rolling, and other sectors.[49] Brown's universal miller had even wider effects. Firms could appropriate cross-industry effects through the sale of capital goods, but even here spinoff firms cut into sales. Externalities were central parts of ongoing technological change.

Many firms used common technological principles to diversify among types of machines so that success in one line occasioned movement into others. One New York directory ad listed "presses of every description, printing presses, hydraulic and screw presses, fly presses, fly and lever presses for jewelers, drop presses or stamps."[50] Diversification sped the diffusion of locomotives and metal-planing machines. Foundries often integrated into machinery production. The iron founder Ephraim Ball had patented plows before inventing mowers and moving into harvesting machinery. Others moved among types of machinery. Harrison Loring and Holmes Hinkley used their expertise in steam engine design and construction to build iron steamships and locomotives, respectively. Several major locomotive firms moved from textile machinery, often producing both, thus solving the puzzle of why locomotive principals invented so much textile machinery. Sellers used its drafting skills to design and produce machine tools for a widening range of uses. Small machine shop owners patented and produced sewing machines. Diversification, however, was not the principal means to achieve benefits of cross-industry invention.

Machinists commonly sold patents. In the all-inventor sample machinists assigned a wider range of patents than did others, and 36 percent of inventive machinery principals assigned patents outside their specialty. For many of them production would have been a distraction from the main line of business, including hat patents taken out by William Sellers and Seth Boyden. A few assigned patents over wide ranges of products, but most did not. Of inventors who assigned any patents, 40 percent of those who patented in two or more categories assigned patents in more than one category. One common path was Singer's: assign early patents and later form a firm, often in a quite separate area from the assignment. About 20 percent of inventors assigned patents to others before they were recorded as machinery principals.

Growth by new firm formation characterized the machinery sector throughout the middle third of the century. Many machinists formed new firms based on an invention or which led to inventions. Background as machinists helped supply universal and particular knowledge that supported innovations and the

Table 5.11. Patent Distribution, Machinists and Nonmachinists

Patent Type	Machinery Principals (%)	All Inventors: Machinists (%)	All Inventors: Nonmachinists (%)
Metalworking	13.8	15.9	3.8
Textiles	9.2	5.1	2.4
Steam engineering	16.5	14.9	9.8
Railroad	5.6	4.1	3.4
Printing presses	3.5	0.8	1.7
Sewing	10.9	5.0	1.6
Agricultural	10.8	13.4	10.3
Woodworking	2.9	3.2	2.3
Other	26.8	37.7	64.6

Sources: U.S. Census Office, Manufacturing Manuscripts from the Eighth Census, 1860 (available in national archives and in state archives in Conn., Del., Md., N.H., N.J., N.Y.); U.S. Treasury Department, "Steam-Engine," 25th Cong., 3rd sess. (serial no. 345), H. Doc. 21, 1839; Edmund Burke, *List of Patents for Inventions and Designs, Issued by the United States, from 1790 to 1847* (Washington, D.C.: J. & G. S. Gideon, 1847); U.S. Patent Office, *Annual Report of the Commissioner of Patents* (Washington, D.C., 1839–65); directories for over 60 cities; city directories and manuscripts of U.S. censuses of population, 1850 and 1860, accessed at *Ancestry.com.*

Note: Data from the all-inventor sample were adjusted to reflect typical inventors, as in table 4.2.

formation and growth of firms. Some stayed in industries in which they trained; new textile, engine, and printing press firms often spun off from old. Others used production or design convergences to move between industries. Inventors forming new firms often trained in other sectors. Before becoming principals, 72 percent of machinists with sufficiently detailed backgrounds gained training in multiple sectors or in sectors other than their ultimate specialties. Such training was essential in expanding the range of machinery.

Machinists and Ongoing Innovation

What, then, was the role of machinists in technological change in the middle third of the nineteenth century? Four conclusions map out an answer.

1. Machinists fostered invention. They were important inventors, with about three-tenths of the economy's patents from 1836 through 1865 and considerably more in mechanized industries. Invention was common within machinery firms. Machinists' inventions were decisive in ongoing mechanization. They aided the invention of others by perfecting and producing mechanisms. They also commercialized new machines.
2. The content of machinists' invention depended on their place in the machinery sector. Specialized firms were parts of networks involving machine users,

and machinists in such industries centered most of their invention on the needs manifested in these networks. In so doing, they sustained technological change within their industries.

3. Machinists were decisive in diffusing and developing production techniques that overcame barriers to the fabrication of complex machinery. Because of the convergent problems faced by many firms, inventions for one sector could be applied to many others. Such inventions spread more rapidly when firms sold machine tools. By the late 1840s machine tool firms arose based on technologies emanating from firearms, textiles, engines, and other industries.
4. Machinists extended the range of mechanization by developing new products, building on design principles common to some or all machines. They commercialized new products by diversifying and especially by forming new firms. Much of the growth of the machinery sector came through the development of new kinds of machinery and practitioners.

Machinists, in short, had become a technological center, which fostered growth and innovation across wide ranges of the economy. Their effects concentrated on mechanization; if industrialization was decisive for economic development, so were machinists. Machinists contributed to civil engineering improvements, electricity, chemicals, and raw materials, but others led such innovations, learning through their own networks. Machinists formed an important technological center, but they did not monopolize cross-industry learning.

In assessing how machinists affected ongoing technological change, think of development occurring from the outside in and from the inside out (see fig. 5.1). Initial development took the form of largely independent processes on the periphery of the machinery sector, each connecting machine users to related machine producers. The first specialized machine producers often worked in shops connected to machine-using firms. They were parts of the machinist occupation but had little connection with machinists in other sectors. By 1830 many had ventured deeper into the machinery sector by forming machinery firms, the products of which diffused to many firms. In part ongoing development after 1835 deepened particular networks, at times spinning off machinery firms that came to lead these networks. The need for machine tool improvements within many networks led machinists to move further toward the sector's hub, ultimately through sale by machine tool firms.

Metalworking capabilities at the hub formed and spread, grounded in relations among machinery firms that were buying and selling machine tools,

engines, shafting, and measurement devices and in the movement of workers among firms. Such relations linked industries, ultimately becoming dense networks of their own. This led to two kinds of movements from the inside out. Techniques developed for one machinery use spread to others, increasingly by sale from machinery firms. In this way machine users benefited from feedbacks within the machinery sector. In addition, new products formed new machinery concentrations and new links with firms outside the machinery sector altogether. Farmers, tailors, and shoemakers came to be linked to the machinery sector. Machinists, then, supported ongoing technological change by inventing and commercializing but also by transmitting knowledge to other machinists who, acting on their own, further integrated and extended the machinery sector. Through both intended and unintended effects, machinists were central agents in forming and deepening the mechanical age.

CHAPTER SIX

Science, Mechanicians, and Invention

Even before independence, Americans recognized the promise of scientific knowledge for useful purposes. They understood that craft knowledge was basically different from knowledge of mechanized industry and that the crafts were unlikely to generate such knowledge by themselves. Like their Enlightenment counterparts in Europe, Benjamin Franklin and Thomas Jefferson expected that science, construed broadly enough to include virtually all knowledge of natural regularities, could find great practical significance. But science had to be nurtured by governments and society. On its own invention would develop slowly with frequent setbacks or would languish altogether. Although disagreeing about specifics, leaders sought to develop and disseminate science, encourage education, foster the press, and form a patent system designed to stimulate invention. Later political and civil leaders followed in each track. The hoped-for result was the flourishing of science and the scientifically trained industrial practitioner, who could translate science into innovation.

Such practitioners—or mechanicians, as I have been calling them—developed among engineers and many others. Applied scientists, broadly defined to include those understanding natural regularities and their useful applications in terms of scientific or engineering concepts, formed another technological center. Unlike machinists, applied scientists had many occupations. They could have powerfully stimulated development by overcoming a discontinuity between craft knowledge and the knowledge of the emerging industrial economy. Karl Marx expected such an outcome. He attributed capitalism's revolutionary character to large-scale mechanized production and argued that science underlay the unprecedented advance of productivity. Capitalism generated factories but also the "modern science of technology" through which innovation supported later innovation when knowledge developed for one use spread to others.[1] Capitalist growth thus depended on the development of science.

The question is whether, and how, mechanicians—and hence science itself—had major significance for technological change in the United States before the Civil War. The answer is hardly evident. Beginning with Samuel Slater, many successful innovations depended little on formal science. The reaper, the wood-planing machine, the power loom, and even the discovery of vulcanization depended more on "empirical" knowledge than on pure science. If scientific training mattered, it was not for all innovations. Moreover, in what contexts did science matter? Did it shape occupations that then operated on their own, or was it of continuing importance? In other words, did science begin an economic process that then developed by its own logic, or was it a resource that practitioners regularly and increasingly utilized? If the former was true, science was a means to support infant industries that later needed no crutch. If the latter was so, then institutions supplying scientific knowledge would become ever more integral to industrial development.

Science, as the term was used in the nineteenth century, covered a great variety of knowledge, accessible to different bodies of people and applying differently among inventions. To understand how science supported invention, this chapter surveys the character of science and its multiple roles in technological change in the antebellum United States. Three kinds of innovators put scientific knowledge to use in ways that fostered innovation: some with sustained training in pure science, others with similar training in applied science, and yet others trained less systematically. Each related to parts of the broader scientific community. Together they led the integration of science in economic life.

A Philadelphia Story and the Variety of Science

In the late 1810s Jacob Perkins's shop was the center for frequent discussions about topics such as how to harden steel for engraving and other purposes, the sort of problem metalworkers had to confront. Eleven men attended most frequently. Perkins already was a widely recognized inventor of nail-making and banknote-engraving machines and casting and die-sinking methods when he moved from Boston to Philadelphia in 1815. He had been admitted to the American Academy of Arts and Sciences but felt unqualified to be a member. He was joined by Coleman Sellers, a mechanic whose testimony helped Perkins win a patent lawsuit and who became a partner in a fire engine factory, and Coleman's 10-year-old son, George. Five precision metalworkers could be called mechanics, though their occupations included jewelry, brass engraving, die sinking, clockmaking, instrument making, and coining. Three others were accomplished in science. Robert Patterson was a

professor of mathematics at the University of Pennsylvania, the director of the U.S. mint, and an author of books and articles on physics and mathematics. The physician James Mease published books on medicine, physical geography, and agriculture, edited the first American edition of two encyclopedias, and lectured in the American Philosophical Society. Trained as a physician, Thomas P. Jones succeeded Coleman Sellers as Perkins's fire engine partner and conducted public scientific demonstrations at Peale's Museum, using young George Sellers as an assistant who "turned the crank handle of the electrical machine, handed him the magic lantern slides, [and] washed chemical glasses."[2]

At first glance the discussions about hardening steel seem to illustrate the "empirical" development of craft techniques. Yet at a time when science was scarce, scientists were present in abundance. Moreover, general principles were proclaimed and general conclusions drawn. George Sellers remarked that lessons learned in Perkins's shop shaped his metalworking practice in quite different applications; he learned not only techniques but also principles that could be applied to many techniques. From Perkins and others Sellers learned a condition of inventors' success: "the necessity of making themselves acquainted with first principles."[3] Understanding these principles directed would-be inventors toward workable solutions. Perkins's guests contributed to Sellers's learning, including an informal class in mechanical drawing that William Mason taught to many young Philadelphians. In the broad nineteenth-century usage of the term, these were scientific lessons. The science discussed by Perkins's visitors was not the frontiers of physics or chemistry; it was a more mundane knowledge of how mechanisms worked. Theirs was not a case of "pure" science creating knowledge that transformed production. A different understanding of the character of knowledge and the mode of its diffusion is needed.

Techniques existed for Perkins and his visitors not only as an awareness of the steps in achieving a particular useful effect but also as knowledge about why some transformations achieved the desired end better than others. This knowledge supplied a conceptual context for understanding a whole variety of techniques. Joel Mokyr calls such knowledge "propositional"; it includes the awareness and conceptualization of natural properties and regularities that underlay the "prescriptive knowledge" directing production. Propositional knowledge included formal science but also engineering principles, experimental methods, measurement standards and implements, mathematics, and modes of visual representation.[4] This notion better identifies the range of knowledge that could direct invention toward plausible solutions.

For propositional knowledge to shape invention, those trying to solve technical problems must have access to it. Access depends on the social distribution and organization of knowledge. If the time and resources required to gain knowledge are high, then the "access costs," to use Mokyr's term, can prevent knowledge acquisition or even block awareness that such knowledge exists. If access costs fall, technological change can accelerate. The significance of propositional knowledge opens up technological change to a host of institutions and agents separated from the uses of that change. Many of these had organization and goals that were quite different from those of commodity production and exchange and as such may have shaped the economy from the outside.[5]

The development of propositional knowledge, its increasingly ready transfer to inventors, and the feedback from prescriptive to propositional knowledge formed a dynamic of fundamental significance for economic development. To understand antebellum innovation requires knowing whether, when, and how widely mechanicians modified techniques and products using knowledge unavailable to practitioners in their own trades. For mechanicians to have so acted, propositional knowledge must have existed, been accessible at acceptable costs, and been used to invent.

Science could only have effects if it had reality. That reality was quite thin at independence, when there were few scientists, little science training, and few scientific volumes written or published in the United States. American science advanced over the antebellum period, and the mechanisms transferring it did as well. Based on his U.S. travels in 1831, Alexis de Tocqueville recognized the kind of science Americans valued. For him the mind divides science into three parts: abstract theory; "general truths that still belong to pure theory, but lead nevertheless by a straight and short road to practical results"; and "methods of application." Americans were highly interested in techniques and the science that illuminated them but less so in abstract science.[6] Tocqueville acknowledged that the parts could develop separately but held that the development of any one would be severely limited if it were isolated from the others. All three developed in the United States, but they did so unevenly, in different directions, and through different means.

By the 1830s domestic institutions spread and generated ideas of pure science, applied science, and techniques, and such institutions deepened by 1860. Diffusion took objective and interactive forms (table 6.1). Books, journals, instruments, and published patents embodied knowledge in ways that could be transmitted without the movement of people, but colleges, scientific and mechanics' associations, and patenting efforts spread knowledge through extraeco-

Table 6.1. Science-Transmitting Institutions and Potential Invention

	Extraeconomic Institutions			
Knowledge Type	Objective	Interactive	Economic Institutions	Potential Inventors
P*ure science and math*	Books, journals, equipment	Colleges, scientific associations, scientific communities	Telegraph and chemicals; publishing industry	Scientists; college-trained; science-based industry
Applied science				
Engineering	Books, journals, equipment	Colleges, mechanics' associations, governmental institutions	Civil and mechanical engineers; infrastructure and machinery; publishing industry	College-educated; engineers; mechanicians; machinists and other mechanical
Applied math	Publications, mechanical drawings	Colleges, mechanics' associations	Engineers, draftsmen	Educated; engineers; draftsmen
Techniques				
Existing	Mechanical dictionaries, publications	Mechanics' association, technical community	Occupations and industries	Mechanicians, science-based occupations
New	Patents, publications	Patent Office, patent agents; technical community, industrial exhibitions	Occupations; capital goods; patent sale; publications	

nomic interactions. Economic interactions also transmitted knowledge, including crafts and services that sold knowledge or ideas. Together, extraeconomic and economic modes of diffusion fostered innovation to a degree that neither mode could have approached on its own.

The United States had been part of the international scientific community from colonial times and continued to be so. Benjamin Franklin and others gained recognition for original research, and 18 colonists were admitted to Britain's Royal Society, but the American colonies were largely recipients of pure scientific knowledge. Much the same was true after independence; Americans contributed, led by Joseph Henry in physics, but were on the receiving end of the great revolutions in physics and chemistry. Americans read avidly. European publications and modestly modified American editions were common and widely used in colleges and elsewhere. Travel and international training brought Americans into contact with leading European scientists. A small group of U.S. scientists, numbering 700 to 800 in 1845, was at the center of the spread of pure science. By 1830 they were often professionals, employed by colleges and medical schools, state geological surveys and other government work, or as physicians. They published widely, edited journals, and associated in urban scientific societies. American publications multiplied, led by Benjamin Silliman's *American Journal of Science and Arts,* issued continuously from 1818. Scientists interacted with a considerably broader community. Colleges offered the most systematic education in science and mathematics; by the 1830s students in liberal arts colleges typically studied mathematics, geology, chemistry, physics, and botany, though texts did not meet European standards. The lyceums that flourished from the late 1820s brought a combination of education and entertainment to a wider audience. Numbering nearly 3,000 in 1834, they presented speakers and at times whole courses to the public, often featuring demonstrations by prominent scientists. Mechanics' institutes arising from the 1820s did much the same.[7]

Contemporaries who argued that science directed technical improvements typically focused not on frontier physics or chemistry but on applications of well-known scientific ideas to useful ends. Engineering and other applied science expanded rapidly in the early nineteenth century. Like pure science, it investigated natural regularities, developed conceptual systems and experimental methods, and spread through publications and interactions in educational, professional, and public settings. Yet it had its own subject matter, categories, and to some degree methods. It spread through different publications, professional interactions, and civil organizations. Edwin Layton called science in its pure and applied (or technological) forms "mirror-image twins" because each attempted to understand

regularities of nature but with different objects and methods and in different communities. These communities began to separate in the early nineteenth century.[8]

In applied science, as in pure science, the United States benefited from the explosion of European advances, beginning with the great *Encyclopedia* of Denis Diderot and Jean d'Alembert, whose 17 volumes and nearly 3,000 engravings included science but also artisanal practice. Its commercial success spawned emulators, including more specialized attempts to apply science to production. While scientific texts often alluded in passing to useful applications, the applied literature focused on techniques and the principles through which they were understood, often with extensive examples. John Nicholson's *Operative Mechanic* began with a short discussion of forces, then turned to elementary mechanical principles of machines, their use in gearing, and various sources of power, and concluded with applications to various industries. The key categories concerned power, its transmission to perform useful work, and the strength of materials. Such publications included analyses of matter and motion, complete with formulas, and descriptions of techniques, including Nicholson's drawings of the Maudslay lathe.[9]

The most important early American contribution was Oliver Evans's 1795 *The Young Mill-wright and Miller's Guide.* By 1860 it had gone through 15 editions. Developing from an article illustrating his flour-milling invention, the book began by discussing mechanical and hydraulic principles and widely used mechanisms such as gears, bearings, waterwheels, and milldams. Evans learned from wide reading and sustained experimentation. Occasioned by his engine, *The Abortion of the Young Steam Engineer's Guide* extended his analysis to steam power.[10] Evans exemplified the dual products of the mechanician: major inventions and the discovery and publication of principles. He recognized deficiencies in his knowledge. Shortly before his death in 1819, Evans, in conversation with Coleman and George Sellers, recalled how the lack of published technical sources had limited his invention. The younger Sellers noted that "the want of published mechanical works that Mr. Evans complained of so much did not begin to be supplied until some years after his death. It was not until 1825 that Nicholson's *Operative Mechanic* was published in England." An American edition was published a year later in the United States, complete with descriptions of American lathes with slide rests, which had been exhibited the previous year.[11] By 1830 Americans published similar works, including Zachariah Allen's *Science of Mechanics.* Jacob Bigelow's 1829 *Elements of Technology* contained a chapter on machinery depicting ways to change velocities and form of motion of machine parts, to control the force exerted through flywheels and governors, and to exert force through mechanisms such as the toggle joint. More sophisticated books

developed principles of kinematics, strength of materials, and civil engineering. In 1831, George Sellers could not find a standard British mechanical dictionary in New York or Philadelphia, but by 1851, when *Appleton's Dictionary of Machines, Mechanics, Engine-work, and Engineering* was published, Americans used a wide array of engineering books. Applied science extended to forms of analysis and depiction of discoveries, especially the "practical geometry" embodied in books on mechanical drawing.[12]

Engineering journals expanded from the mid-1820s. Americans imported British journals such as the *Mechanic's Magazine.* From about 1810 the *North American Review* published articles on applied science and machinery. Specialized journals contained more sustained information. The most important among them through 1850 was the *Journal of the Franklin Institute,* published from 1826. A key goal of the journal was to spread technical knowledge outside of craft training. In its first issue Thomas P. Jones, its capable editor and one-time Perkins partner, put the goal in world historical context: "The age of secrets in arts and trades, has nearly passed away . . . a free and open intercourse is acknowledged to be the best policy." To spread knowledge required something outside the trades, and the journal would "enable the artisan and others, to obtain information which might otherwise be sought in vain."[13] It reprinted reports on pure science from prominent journals in England, France, Germany, and Scotland—including articles on electrical experiments by Michael Faraday and Charles Wheatstone—and over time added American research on electricity, chemistry, and meteorology. About 1,000 copies were printed monthly in 1832 and considerably more a few years later.[14] The *Scientific American,* published from 1845, gained preeminence at midcentury. According to its publisher's diaries, it sold 24,000 copies weekly by 1859, making it the world's most widely read mechanics' journal.[15] A revolution in techniques was accompanied by another in publication.

Publications included extensive descriptions of new techniques. The *Journal of the Franklin Institute* reported at length on hardening steel, canal and railroad construction, and the strength of materials. In 1827 it presented Boulton and Watt tables relating its engine's horsepower, piston area, and strokes per minute; a series on woodworking; and articles on saw plates, gun barrels, spring hardening, locomotives, and the "American" improvement on Maudslay's slide rest. In 1826 it began to publish short descriptions and claims to originality for each U.S. patent, and for the first time the American public could explore every patent issued. Jones commented on the invention's quality, often identifying its usefulness in discriminating ways; some were inferior to others, too complex, usable only in rough work, or of limited applicability.[16] Its extensive section on inventions, in-

cluding foreign patents, was widely read. After 1845 the *Scientific American* listed patent claims and, for a subset, specifications. Connected to the Scientific American Patent Agency, it had more articles on inventions, including a column of correspondence with inventors.

Interactions spread knowledge of applied science. Collegiate engineering education was only coming into being and largely at one institution, the U.S. Military Academy at West Point. Formed in 1802, the academy became the premier scientific and technical college in the country from 1817. Its students learned mathematics, physics, geology, chemistry, mineralogy, civil engineering, surveying, and drawing. Other colleges started engineering programs, including Rensselaer Polytechnic Institute (RPI) in Troy, New York, and the Norwich Academy in Norwich, Vermont.[17]

Mechanics' institutes were of wider importance. They were established in the 1820s and 1830s in Philadelphia, New York, Boston, Providence, Portland, Baltimore, Paterson, Cincinnati, and other cities, about the same time as British institutes were forming. Their goal was to diffuse useful knowledge to the producing classes, with the expectation that such knowledge could not be gained on the job. Philadelphia's Franklin Institute led the way, formed in 1824 out of conversations between Samuel Merrick, a successor to Jones in Perkins's fire engine firm, and William Keating, a University of Pennsylvania science professor. From the start the institute successfully attracted mechanics, merchants, professionals, and scientists; it had 600 paid members by the end of 1824 and 2,500 in 1839. Its widely popular lectures were delivered by appointed professors in natural philosophy, chemistry, engineering, architecture, and mechanics. Its school provided regular instruction; the mechanical drawing program enrolled 50 students within a year, though mathematics courses were sparsely attended. Its library and museum included patent models. Its fairs displayed inventions and products of American manufacturers to 15,000 people in 1825, 40,000 in 1838, and as many as 100,000 by the 1850s.[18] Its Committee on Inventions published assessments of ammunition, steam engines, locomotives, canals, carpeting, and other inventions. Specially appointed committees examined key mechanical problems, most important among them steam boiler explosions. It published a journal and organized a high school.[19] Through it and other mechanics' institutes, tens of thousands of workers and small owners gained technological knowledge and interacted around technological interests. Industrial fairs disseminated knowledge more widely yet.

Private interactions also spread scientific and technological knowledge. Learning occurred on the job in occupations such as clock making, instrument mak-

ing, machinery, and engineering. Off-the-job interactions began early, especially in cities, such as when John Fitch discussed his steamboat with Oliver Evans in the 1790s. As manufacturing grew, so did such interactions. The visitors to Perkins's shop in 1811 were integral to the Philadelphia technological community; many led the Franklin Institute, and several published widely. Informal interactions within the mechanical community supported mechanics' institutes, generated demand for publications, and supplied authors. Institutes and publications in turn supported the informal community. Mechanicians originated in relation to other mechanicians, as mediated by a dense system to collect, store, and diffuse technological information.[20]

The decade from 1826 to 1835 marked a transition in spreading pure and applied science. Scientific and engineering publication increased significantly, including textbooks, engineering reference books, and journals. Science and mathematics education became much more central to the college curriculum, and textbooks and equipment improved. Some colleges presupposed that students had already learned algebra, which high schools and academies increasingly provided, along with exposure to science. Mechanics' institutes sponsored lectures, courses, and exhibitions.[21]

The upsurge of science had substantial autonomy from the economy. Clearly, science required funding, and so it was economically conditioned. But governments, colleges, mechanics' institutes, lyceums, and fairs were essentially nonprofit organizations, often relying on volunteer labor. Much scientific knowledge was open access, with no payment to scientists. Technological publications rarely brought significant returns. Applied science responded to practical needs in a general way and at times specifically, as in the Franklin Institute's studies of waterwheels and boilers. Some wealthy industrialists became leaders and benefactors of colleges and voluntary organizations. Although economically conditioned, science relied on its own institutions that did not directly respond to economic imperatives. If scientific knowledge significantly affected innovation, then civil society and governments helped account for economic development.

Science and the Potential for Invention

Superior scientific knowledge could stimulate invention by reducing its costs or improving the prospects for success. The development or dissemination of knowledge each could have provided the stimulus. Knowledge did develop, especially later in the period. New chemical and electromagnetic knowledge had clear implications for some production processes. Advancing geological knowledge

mattered less for manufacturing than for civil engineering and resource extraction. Applied science grew markedly. Mathematicians and engineers undertook systematic studies of the theory of machines, including ways to translate motion from one form to another, with a goal of determining the best way, for example, to change from continuous rectilinear motion to alternating circular motion. The Cambridge professor Robert Willis published a widely influential study in 1841. Scientists and engineers studied friction and the strength of materials. These studies were less of a jump from craft knowledge than were such new fields as electromagnetism, but they pertained to a wider range of productive activities.[22]

Most innovations were based on established knowledge, not new developments. Here access was key. Access costs rested on the availability of knowledge and the capabilities of individuals to use it. From the 1820s growing dissemination of scientific knowledge reduced access costs. *Diffusion* was the catchword of the day; societies were formed to facilitate it, and a book series took the title. The spread of technical knowledge developed what Edward Stevens called "technical literacy": the mastery of alphabetical, mathematical, scientific, and spatial forms of expression through which technological knowledge was formulated and transmitted.[23] Such mastery increased capabilities to understand science; aided workers in getting, keeping, or improving jobs; and supported invention. Mechanics, hydraulics, mathematics, and mechanical drawing formed a conceptual system and a method within which problems could be posed and solutions explored. When Nicholson began *The Operative Mechanic* by stating that "the most elaborate pieces of mechanism . . . are in the eye of the practical man mere elegant modifications and combinations of a few simple principles," he was inviting readers to acquire knowledge that pertained not only to the steam engine and mule but also to inventions that had not yet been made.[24] Both the concepts and the method existed outside any actual devices and could be transmitted independently. The content of knowledge could illuminate choices in the design of implements, such as how to achieve a desired form or periodicity of motion or how to overcome resistances. Drawing supplied a way to depict mechanical problems precisely. Systematic experimenting allowed inventors to assess the viability of potential solutions, directing their efforts in more promising ways. If inventions were new combinations of existing knowledge, applied science expanded the range of knowledge and gave it a form capable of conceiving and assessing claims about usefulness.

Propositional knowledge was unequally available, conferring advantages to inventors with easier and cheaper access. Availability varied over time, among locations, and among individuals. More extensive diffusion benefited later inven-

tors. Urban residents benefited from proximity to colleges, scientists, engineers, libraries, and mechanics' institutes. People varied greatly in their capacity to use scientific knowledge. Already by 1827 Thomas Jones argued that artisans could not understand the scientific articles in the *Journal of the Franklin Institute*.[25] Scientists and those they taught could most readily comprehend such knowledge, complemented by those in scientific occupations. Applied science was more accessible, but because it involved a complexity of reading beyond the education of most artisans, individuals with knowledge of civil engineering, electricity, chemical manufacturing, or machine design were best prepared to absorb it.

Major innovators document the importance of scientific knowledge and modes to acquire it. One-quarter of them attended college, and another fifth attended high school (see tables 4.6, 4.10, and 4.11). A slight majority of mechanicians did not have a college education, though only a third were limited to grade school. Collegians were especially important in chemical, electrical, and construction innovations; mechanicians also concentrated on metalworking, transportation, instruments, and power. Major innovators with scientific and mathematical knowledge were common, expanded substantially, and gained their knowledge through different means.

That scientific knowledge could have shaped invention does not mean it did. Some inventors with scientific knowledge also could have learned on the job or from inventing. Because different groups held knowledge relevant for different kinds of invention, establishing the role of science requires studies of various technologies and practitioners. Propositional knowledge should have had the greatest effect among those mastering it most fully and in applications that it illuminated. If so, innovation should have differed among those immersed in pure science, those trained in applied science, and those with less exposure to either.

Pure Science and Invention

Joseph Henry, the physicist and organizer of the Smithsonian Institution, advanced two theses about the relation of science and industry. He argued that invention, or at least major inventions, resulted from scientific advance: "The loom and the plough, the wind mill, the water wheel, and the steam engine are all instances of the application of the principles of science to practical purposes and each has received from the abstract labours of the Philosopher their greatest improvements."[26] On the other hand, because of "the feeling common to men of science, which disinclines them to secure to themselves the advantage of their discoveries by a patent," scientists left to others the practical application of sci-

ence, which was "in a scientific point of view of subordinate importance."[27] Together the theses argue for the role of the mechanician because if science was essential but scientists focused on the abstract, invention was the domain of the scientifically trained practitioner.

Both contentions are debatable. Shortly after Henry advanced the second claim, Charles Page contested it by listing eight American scientists who also patented. Page himself illustrated the link; he was a notable contributor to electromagnetic science, a patent examiner, a patent agent, and an inventor. Yet Page's scientist-inventors illustrate Henry's claim: they either had little importance for invention or gained importance by moving into engineering. Page's own inventions, including an electric locomotive, had little success.[28] In fact, scientists did not invent much and often did not want to. Led by Henry, many acted to promote science as an intrinsic goal, making little effort to develop useful effects. They spread their research publicly, consistent with the open-source availability of knowledge practiced in Europe. Although scientific knowledge, unlike inventions, could not be owned, employment opportunities and scientific recognition proved sufficient to stimulate discovery and publication. Major publications such as the *American Journal of Science and Arts* concentrated on science and did little to promote the useful arts. Leading scientists hardly invented at all. Henry, Alexander Bache, Benjamin Silliman Sr., and Benjamin Silliman Jr. received no patents through 1865. One of Page's examples is a case in point. Robert Hare was trained in chemistry and developed a blowpipe to obtain very high heat. He patented a brewing method when managing his father's brewery and later patented his blowpipe and a manure-treating process. When Hare became a chemistry professor at the University of Pennsylvania, he published in scientific journals, edited chemistry books, and developed scientific apparatus. His basic focus was clearly on science. He was the most prolific contributor to the *American Journal of Science and Arts* before 1860. Virtually none of that journal's other major contributors patented at all.[29] If science was to affect invention, it was not through invention by scientists.

Henry's contention that science itself drove invention was questionable because it ignored the role of knowledge transmitted in economic interactions in inventing plows and looms and made claims for pure science that were outcomes of applied science, including turbine improvements in waterpower. But pure science did play a role. As Henry's examples suggest, science could shape invention through its methods and its content. Its methods included experimental techniques, used so effectively by John Smeaton, and mathematical arguments, though these involved at least as much applied science as pure science. The con-

tent of science varied widely in terms of its usefulness. Henry played a role in the clearest example of the indispensability of science, the telegraph. As will be detailed later, the electric telegraph was a radical innovation resting on recent developments in electrical knowledge. Samuel Morse would not have conceived his invention without scientific knowledge gained as a student of Benjamin Silliman and through a New York lecture series. Nor would his invention have become practical without the assistance of Charles Page and the chemist Leonard Gale.[30]

Developments outside physics played less clear roles. The strong interest in geology and geological surveys advanced internal improvements and mineral discoveries and may have illuminated a narrow range of inventions. Jacob Cist's studies of the geology of Pennsylvania anthracite deposits led him to mine anthracite and invent a stove and a printer's ink using that material. Chemical knowledge had wider potential. Although it was little used in much industrial chemistry, such as brewing and soapmaking, chemical science was utilized more fully elsewhere. Samuel Wetherill utilized chemistry studies at the University of Pennsylvania to become a chemist in the family firm, where from the 1850s he developed processes for producing zinc oxide directly from the ore. George Mowbray applied chemistry training in England, France, and Germany to manufacture drugs and refine oil. He used nitroglycerin in drilling oil wells and became a leading nitroglycerin producer.[31] Chemists often analyzed materials. Benjamin Silliman Jr. wrote an influential essay on petroleum. The Ordnance Board, the testing arm of the Ordnance Department, employed chemists to systematically analyze gunpowder and gunmetal.[32]

Industries that depended on advances in pure science were exceptional, but scientists played a broader role by spreading knowledge. Colleges provided the arena for an increasingly wide, sustained exposure to science and mathematics. Science education improved after independence. By the 1830s colleges employed professional scientists, and students typically took sequences of courses in mathematics and the sciences. Texts and instrumentation also improved, often authored or developed by science professors. Except at West Point and RPI, there was little training in applied science, and even these schools concentrated more on pure science and mathematics. Scientists may have had their biggest impact not as inventors or even as researchers but, rather, as professors and authors spreading current scientific knowledge.

College education and the ensuing career trajectories prepared many to innovate. Among major innovators three-fifths of the college-educated worked in scientific occupations, compared to 24 percent for the high school–educated and 3 percent for those who did not attend high school (table 6.2). Engineers made

up about half of the college-educated in scientific occupations; the rest included nine professors, eight in electrical, chemical, or mineralogical research, and five in medical fields. Noncollegiate inventors concentrated more in mechanical occupations, especially as machinists. Mechanical occupations employed about half of those educated in high schools and seven-tenths of those with lesser educational attainment. Many college-educated inventors remained within the sciences when they changed occupations. Engineers became patent examiners, or professors became industrial chemists, though others went into manufacturing.

Unsurprisingly, the share of mechanicians was much higher among the college-educated. But the far larger share of mechanicians among high school students than grade school students—59 to 22 percent—suggests that more than college was involved. Education created the opportunity to learn outside the classroom, and college and high school students differed only in degree. The intriguing possibility arises that at least two paths supplied propositional knowledge, one through college into scientific professions and the other through high school and work in the machine shop, complemented by scientific learning. The college-educated were much more likely to develop science-based major inventions (measured by those involving electricity, chemicals, water turbines, and scientific instruments) and to write and publish on scientific and technological topics. Two-fifths published, compared to one-fifth for innovators with high school educations and one-twelfth for others. Publication represented an important feedback within the technological community because mechanicians formed a demand for publications and in part supplied that demand.

College fostered invention outside the knowledge it conveyed. Higher shares of graduates entered occupations in which they interacted with others sharing scientific interests, thus continuing their learning. The college-educated more often had positions of authority in firms or occupations and so would be expected to generate a larger proportion of inventors. Yet there can be no doubt that knowledge gained in college aided invention and started many on paths as authors, professors, and lecturers that would deepen their knowledge. The case is clear for the telegraph, for which Morse's art professorship linked him to scientists essential for perfecting his invention. John Stevens and Nathan Read applied experimental procedures learned in college to steam engine invention. Francis Lowell's mathematical proficiency helped him copy British weaving machinery and design textile machines. Eliphalet Nott undertook experiments on the properties of heat, the results of which he used in two dozen stove and boiler patents. Scientific and mathematical knowledge—and not only professional position and contacts—aided invention.

Table 6.2. Major Innovators by Level of Education

	College	High School	Grade School and Lower
Inventors	67	51	154
Average patents	5.87	7.96	6.72
Inventive breadth	2.54	2.78	2.75
Occupational shares (%)			
Agriculture	3.0	2.0	4.5
Mechanical	17.9	49.0	70.8
Other manufacturing	3.0	13.7	16.2
Trade and services	14.9	11.8	5.2
Science	61.2	23.5	3.2
Engineers	38.8	19.6	9.1
Mechanician (%)	86.6	58.8	22.1
Prior invention (%)	29.9	29.4	44.2
Science-based invention (%)	28.4	13.7	13.0
Technical and science authors (%)	38.8	19.6	7.8

Sources: Dumas Malone, ed., *Dictionary of American Biography* (New York: Scribner, 1937); *National Cyclopaedia of American Biography* (New York: J. T. White, 1898–); *A Biographical Dictionary of American Civil Engineers,* 2 vols. (New York: American Society of Civil Engineers, 1972 and 1991).

Note: Percentages are shares within each type of education. Comparisons include inventors for whom sufficient information existed. Grade school and lower included some who went to high school or college but whose biographies do not mention this fact. Engineers include all who were engineers at any point in their lives but not necessarily at the time of their first major invention. Science-based invention includes electrical, chemical, water turbines, and scientific instrumentation. Authors include those who published scientific and technological books and articles.

Nevertheless, there is little evidence that advances in pure science induced invention outside the telegraph. Geology, botany, and astronomy had limited effects. Chemistry supplied experimental methods, but the experiments creating durable rubber differed basically from those of the chemical revolution. New science had little impact on mechanical invention. Established science was more important. Yet Eli Whitney was an accomplished mechanic before entering Yale, which likely informed his cotton gin invention more than his college education did. John Howe's rubber invention used chemical knowledge but failed; Charles Goodyear succeeded with much less training. Howe's pin-making machine, important in itself and for its automatic principles, rested less on his scientific knowledge than on the community of mechanics, including workers in the Hoe press shop who helped perfect the machine and the Waterbury brass makers who manufactured it. Collegians and mechanicians did acquire scientific methods, a mathematical facility, the capacity to apply science, and opportunities to interact with the scientifically trained. These capabilities, falling as much in the domain of applied science as in that of pure science, fostered invention even when pure science did not.

Engineering and Invention

Involving science, mathematics, and their application to practical ends, applied science was too complex to be mastered by large numbers of people in their spare time. But some specialized in it, working as civil engineers, mechanical engineers, electricians, and scientists. Civil engineers concentrated on large-scale outdoor public works, notably canals, roads, railroads, river clearance, and water delivery and sewage systems. Well established in eighteenth-century England and France, civil engineering in the United States blossomed in the canal boom begun in 1816 and surged when railroad construction took off after 1830. State geological surveys hired engineers and scientists. The Army Corps of Topographical Engineers and the Coast Survey employed army and civilian personnel in exploration, cartography, surveying, river and harbor clearance, and other tasks. The Ordnance Department supervised national armories and researched armament improvements; ordnance workers and naval engineers linked military and mechanical engineering. Mechanical engineers emerged late in the period from machine shops, railroad repair shops, the navy, and civil engineers.[33] Scientists included specialized occupations such as industrial chemists and professors; many advised infrastructural projects and occasional federal projects such as the steam boiler explosion investigations. A few nascent electrical engineers, usually linked to telegraphy, had arisen by 1860.

City directories supply a sense of proportion. Over 70 civil engineering firms were listed in Boston, New York, and Philadelphia in 1860, and many other engineers worked on infrastructure projects. They probably were the largest group of applied scientists with technological knowledge. Thirty mechanical engineers listed their services in 1860, and others worked in railroad shops and on steamships. Fewer than 10 listed electricians complemented those employed by telegraph firms. Draftsmen, pattern makers, and model makers added to those with propositional knowledge.

How did civil engineers acquire knowledge of mathematics, surveying, drawing, hydraulics, geology, construction, and bridge design? Most were trained in the United States, though sometimes they were taught by British, French, and German émigrés. Many learned in colleges. About one-quarter of West Point graduates worked as civil engineers inside and outside the army, including about 115 in 1837, the antebellum peak. Rensselaer Polytechnic added to the pool from the 1840s. More engineers learned on the job, especially in major infrastructural projects but also in apprentice-like relations to civil engineers. Before 1835 the New York State canal system was the most prominent of these invisible colleges;

its graduates worked inside the state and particularly in the West. Pennsylvania canals formed another. Over three-quarters of chief engineers on public works projects in 1837 had not graduated from an engineering school. Railroads supplanted canals as primary source of training after 1835. Topographical engineers were trained in colleges and as surveyors.[34]

By the character of their job, engineers developed novel solutions to technical problems. Most solutions in designing canals or railroads were not patentable, and others were not patented. The leading engineer John Jervis was trained on the Erie Canal, designed or managed three canals, seven railroads and the Croton Aqueduct, and invented gauges to measure water accumulation, a dominant locomotive design, and a new spillway system for dams but received no patents.[35] Some improvements were patented. Eighteen percent of major innovators with patents were engineers at some point in their professional life.[36] Their occupation shaped invention. Seven concentrated on bridge patents, especially the truss bridge used on roads and railroads; 12 focused on navigation, pumps, and turbines; and 18 improved railroads or steam engines. Altogether three-quarters of the engineers concentrated patents on occupational activities. Robert Fulton used his training as a canal engineer when inventing his steamboat. He combined careful experimental methodology in boat design with mathematical expertise leading to his patent's "exact or mathematical principles" concerning drag, engine power, paddlewheel size, and velocity.[37] His engineering expertise sped up the introduction of steam navigation. Stephen Long graduated from Dartmouth, taught mathematics at West Point, then joined the Topographical Engineers, with whom he explored the upper Mississippi River, the Rocky Mountains, and the Minnesota River from 1817 to 1823. In 1827 he was assigned to help select the route of the Baltimore and Ohio Railroad. The job turned his attention to railroad engineering and his inventive efforts to locomotives (designed with William Norris in what would be a leading firm) and especially to bridge design, for which he received six patents.[38]

Formal mathematics contributed to engineering advances, as the water turbine illustrates. In the 1820s the French engineer Benoit Fourneyron applied mathematics to design the turbine, which overcame efficiency limits of earlier waterwheels. James Francis and Uriah Boyden introduced the turbine in the United States around 1844. Francis, trained in engineering in England, was chief engineer of the water system that drove the Lowell mills. Boyden, the son of one well-known inventor and the brother of another, built railroads and ran a consulting engineering service. Recognizing efficiency limits associated with Fourneyron's simplifying assumptions, they applied hydraulic theory and systematic

experimentation to design turbines with efficiencies as high as 88 percent. Boyden took out six turbine patents, and Francis published the widely consulted *Lowell Hydraulic Experiments.*[39]

Bridge design exemplified engineering invention. Bridge construction expanded as roads and railroads developed, and new truss and suspension bridge designs followed apace. Bridge invention increased with infrastructural expenditures (table 6.3). In a sample of 125 bridge inventors, patents grew from under 6 per decade before 1826 to 19 from 1836 to 1845 and 85 from 1856 to 1865. Five-eighths of those with known occupations were engineers or bridge builders. Some learned in colleges or polytechnics, including John Roebling in Berlin and many West Point engineers. Engineers were virtually the only inventors to receive more than one bridge patent. Their other patents were complementary; if construction, canals, and railroads are added, engineers averaged 2.6 civil engineering patents. Some inventors used patents in their own firms, including Wendell Bollman, who in 1860 advertised his services: "Civil and Constructing Engineers . . . Manufacturers of Bollman's Patent Iron Suspension Trussed Bridge, for Railways and Common Roads."[40] Others assigned patents, though only 22 percent assigned bridge patents to others.

Understanding the generality of invention among early engineers is difficult because they typically did not organize firms or advertise in city directories. *A Biographical Dictionary of American Civil Engineers* provides some insights. It lists 79 engineers who were active through 1835. The vast majority were involved professionally in canal, river, harbor, sanitation, road, and railroad construction and design. Just under 50 percent of them had graduated from college, 46 percent of whom graduated from the U.S. Military Academy.[41] Engineers innovated much, but only 18 percent patented. The share was just as low among college graduates as among others. Their patenting paralleled their engineering activities, including bridge designs, a waterproof cement, and a mechanical drawing instrument. The most prolific among them, John L. Sullivan, was an engineer and superintendent for the Middlesex Canal Company who invented a steam towboat and a series of propeller and engine improvements. While surveying for another canal, he investigated anthracite deposits and invented an anthracite furnace. Turning to urban engineering, he patented two improvements for street pavement and developed pumps while boring wells for the New York City water supply.[42]

Unlike civil engineers, who formed a well-defined occupation by the 1840s, mechanical engineers were a loosely defined group who shared an ability to design machinery and depict designs in drawings. Whereas the biographical dictionary sponsored by the American Society of Civil Engineers offered a content-

Table 6.3. Bridge Inventors, 1790–1865

	All	Machinists	Science and Invention	Other Manufacturing	Trade and Service	Farmers
Inventors	125	3	34	6	6	5
Share by occupation (%)		5.6	63.0	11.1	11.1	9.3
Average bridge patents	1.33	1.00	1.65	1.17	1.00	1.20
Average patents	2.94	6.00	3.71	2.17	6.67	2.40

Sources: U.S. Patent Office, *Subject Matter Index of Patents for Inventions Issued by the United States Patent Office from 1790 to 1873, Inclusive* (Washington, D.C.: Government Printing Office, 1874); U.S. Patent Office, *Annual Report of the Commissioner of Patents* (Washington, D.C., 1839–65).

specific definition, the equivalent volume of the American Society of Mechanical Engineers defined its subjects broadly enough to include "not only the designers of and practitioners in machinery, but also teachers, publishers of engineering works, entrepreneurs, and a fair number of what today might be considered simply inventors and tinkerers."[43] In an 1852 *Scientific American* ad Charles Copeland described himself as a "Consulting and Mechanical Engineer" who "superintends the construction of steam vessels, and steam engines and machinery of every description; specifications and contracts prepared; also, general plans and drawings in detail furnished."[44] Copeland had been a government-appointed naval engineer and superintended private steam engine firms, but he applied his knowledge to all machinery. Others came from railroads or engine and machine shops. Using experience at the Colt Armory, Charles Richards advertised as a "designer of machinery & mechanical draughtsman."[45]

Urban engineers grew rapidly after 1840. By the late 1840s they began to list their services in business directories, including 93 engineers in 8 cities around 1850. Civil engineers predominated, joined by a few mechanical engineers. Around 1860 directories listed 161 engineers in 19 cities. Mechanical engineers expanded to 36, frequently doubling as civil engineers and sometimes as machinists, draftsmen, model builders, or patent agents. Civil and mechanical engineers had different inventive proclivities. As a study of 80 civil engineers and 49 mechanical engineers reveals, both groups invented, but the 61 percent share of mechanical engineers with patents was twice as high as that of civil engineers (table 6.4). Inventors from both groups averaged five or more patents, about the same as engineers in the major innovators sample. Their inventive breadth was also about the same. Civil engineers focused invention more in construction and transportation, whereas mechanical engineers spread their patents broadly. Seventy percent of engineers assigned patents, and 60 percent assigned to others.

Table 6.4. Patenting by Urban Engineers and Electricians

	Civil Engineer	Mechanical Engineer	All Engineers	Electricians
Inventors	80	49	129	26
Share with patents (%)	28.8	61.2	41.1	53.8
Average patents	5.61	5.00	5.26	2.36
Inventive breadth	2.78	2.83	2.81	2.14
Patents, maximum category	2.70	2.50	2.58	1.93
Assignments				
Researched	17	24	41	7
Any assignment (%)	58.8	79.2	70.7	57.1
Assigned to others (%)	52.9	66.7	61.0	57.1

Sources: U.S. Patent Office, *Subject Matter Index of Patents for Inventions Issued by the United States Patent Office from 1790 to 1873, Inclusive* (Washington, D.C.: Government Printing Office, 1874); U.S. Patent Office, *Annual Report of the Commissioner of Patents* (Washington, D.C., 1839–65); city and business directories for 60 U.S. cities, 1845–65.

Note: All civil engineers who maintained that occupation for at least four years were studied. To get larger numbers, all mechanical engineers listed as such at any point through 1861 were examined. Electricians include those listed as such and as telegraph apparatus makers.

By the 1860s electricians were also listed in city directories, selling telegraph instruments, batteries, electromedical devices, and their own services. About half of them patented. They concentrated their inventions on their occupation, patenting telegraph instruments, batteries, and lightning conductors and applying electricity to medical devices, metal amalgamators, and the subject of Edison's first patent, recording votes. Many tried to make and sell their inventions; those who assigned patents mostly did so for nonelectrical inventions.

Professional applied scientists were important inventors in infrastructure and the telegraph, but they were so few and their attention was so concentrated that they could not be expected to lead invention in most industries. If applied science shaped invention widely across the economy, it did so through larger numbers of mechanics gaining some scientific knowledge.

The Wider World of Invention

Seven-tenths of major antebellum innovators neither attended college nor were employed as engineers and hence could not acquire propositional knowledge through such avenues. Yet less-educated inventors averaged more patents, patented more widely, and received more patents in the maximum category than their better-educated peers (table 6.5). A larger share (39 vs. 30 percent) invented before the appearance of their major invention. Apparently, major inventors

Table 6.5. Varieties of Inventors

	College and Engineering	Not College and Engineering	Mechanician	Mechanical	Other
Inventors	82	199	59	98	42
Share of inventors (%)	29.2	70.8	21.0	34.9	14.9
Average patents	5.76	7.23	9.14	6.86	5.40
Inventive breadth	2.44	2.85	3.54	2.80	2.02
Patents, maximum category	3.77	4.60	5.20	4.49	4.00
Patents, other categories	1.99	2.63	3.93	2.37	1.40
Prior invention (%)	30.5	39.2	45.8	38.8	31.0
Technical and scientific authors (%)	35.4	9.5	25.4	0	9.5

Sources: See table 6.2.

without systematic scientific training suffered no insurmountable disadvantages in their fields of invention.

Innovators without systematic training in pure or applied science typically had less scientific knowledge and greater difficulty in acquiring it than did the college-educated and engineers. Learning off the job could compensate. Recognizing this, Thomas Jones wrote an "Artisan" series in the *Journal of the Franklin Institute,* the goal of which was "to diffuse some acquaintance with its [science's] principles and processes, among practical men, to whom it may prove a valuable auxiliary, in their respective occupations."[46] Classes in mechanical drawing and writings on testing procedures, kinematics, and the strength of materials had the same effect. Many without college or engineering education acquired propositional knowledge in such ways. Thirty percent of them qualified as mechanicians because they studied scientific literature or learned science from interactions outside the workplace. They averaged more patents and greater inventive breadth than any other set of innovators.[47] Some used fundamentally new kinds of knowledge to invent, including Royal House, who studied intensively to gain knowledge needed to develop his printing telegraph. Many concentrated on mechanical components. Ezra Cornell worked closely with Morse, built a machine to lay pipe for telegraph lines, and then developed a mode of insulating cables (and became one of the telegraph's biggest promoters). He required some knowledge of electricity but more like that of today's electricians than electrical engineers, and he learned on the job. Similar collaborations aided mechanics such as George Wilson, who formed a chemical manufacturing partnership with Eben Horsford, the Rumford Professor of Chemistry at Harvard.

Journals advanced invention. The inventor of the firearm percussion cap, Joshua Shaw, already had some knowledge of the chemistry of explosions when he submitted questions to *Journal of the Franklin Institute* editors concerning scientific notation and tests for the purity of chemicals, reflecting that "these simple inquiries may cause those learned in chemistry to smile." Taking the high road, the editors responded that we "are not inclined to smile at the difficulties which the practical man frequently encounters from the want of theoretical knowledge," identified four equivalent names for the compound in question, and relayed a testing procedure. The Franklin Institute went further by charging its committee on invention, in its first such effort, to assess the quality and usefulness of Shaw's invention, which the committee endorsed after testing it at a federal arsenal.[48] Such judgments became commonplace; *Scientific American* offered advice about the soundness of inventive ideas to over a dozen prospective inventors each week.

Interactions within mechanics' institutes also directed invention. Timothy Claxton, trained as a whitesmith and machinist in London, where he studied drawing, mathematics, natural philosophy, and chemistry, helped found the Boston Mechanics' Institution in 1826. Working with the Lyceum founder, Josiah Holbrook, he helped establish the Boston Lyceum soon after. He lectured on science, and, after Holbrook noted the need for cheap instruments for scientific demonstrations to broad audiences, Claxton developed and manufactured an air pump, which he patented in 1835. He sold several hundred pumps, packaged with portable cases, illustrations, and explanations. The very object of Clayton's invention rested on the self-organization of mechanics.[49] Others lectured on chemistry, including one Colonel Coult, though his topic had little to do with his famous revolver. Zachariah Allen began to study steam engines to prepare a lecture for the Providence mechanics' institute. His study revealed the possibilities of using the expansive power of steam and the need to regulate the steam inflow. Allen's solution developed into his engine cutoff patent of 1834.[50]

Mechanics could not easily interpret the new technical literature without scientific training. Mechanics' institutes brought together talent that could overcome this limit. From 1824 through 1831 the Franklin Institute's journal listed 67 managers and members of committees. Almost one-third of them warranted an entry in the *Dictionary of American Biography,* including four scientists and science professors; six engineers, architects, and doctors; six artisans or manufacturers (machinists, chemists, die sinkers, engine makers, and tanners); and the editor of the *Journal.* Eighteen managers or committee members received patents through 1846, the large majority after the institute formed in 1824. Other bought

patents, including the sugar-refining inventions secured by Samuel Merrick, one of the institute's founders. Clearly, the institute attracted inventors and cultivated this interest.

The institute formed collective research efforts that anticipated twentieth-century R&D. The Committee on Inventions conducted methodical tests on the form and efficiency of waterwheels. It sent out a prospectus to secure private funds, designed and constructed a testing facility; called on the volunteer labor of professors, engineers, and machinists; and recorded almost 1,400 experiments. Published in 1831, the results were applauded in England and the United States for their content, accuracy, and the large-scale, cooperative form of the endeavor. Success positioned the institute to head national research into steam boiler explosions. The institute proposed systematic experiments when it learned that the federal government was pursuing similar lines of research. Securing federal funding in 1830, a large committee of scientists and manufacturers conceived a subtle set of experiments and designed, built, and calibrated testing equipment. Its report, published in 1836, carefully analyzed steam pressure and its relation to explosions, pressure-testing devices, and the strength of boiler materials. The report advocated federal inspection of boilers and standards for safety devices and personnel training, responsibilities it would take the federal government 15 years to accept. Innovation continued during the Civil War, when the institute, now led by William Sellers, studied screw threads and successfully established a U.S. standard. Some investigators used their work in later inventions, such as James Rush's 1837 steam boiler patent and two 1838 patents to strengthen iron and steel issued to Walter Johnson, who headed the strength-of-materials experiments.[51] Although the institute showed that organized research could effectively unite the knowledge of scientists, engineers, and manufacturers, large-scale research remained exceptional.

Learning from publications and mechanics' organizations did not provide inventors with scientific knowledge to match that of collegians or engineers. Even if they were in close contact with scientists, their invention built more on learning on the job and in interactions among mechanics. Consider one of the mechanics who met at Perkins's shop. Matthias Baldwin was an apprenticed jeweler who ran his own shop from 1819 to 1825. Over the period he formed ties with Perkins's other visitors and many Philadelphia mechanics. His interactions deepened in 1823, when he helped organize the Franklin Institute; later he sat on the board of managers. Although he joined its committees on invention and steam boiler explosions and worked closely with Thomas Jones and Alexander Bache, he never studied science systematically. In 1825 he formed a partnership with Da-

vid Mason, who made scientific instruments and machinery and whose brother taught mechanical drawing. The two made bookbinding tools, engravers tools, and some of the first U.S. slide lathes. His partner already had two patents, and he and Baldwin patented a machine to engrave plates for printing calico. Informed by the study of technical publications, Baldwin's 1829 patent improved the hydrostatic press of the English machinist Joseph Bramah. Baldwin entered engine making, completing his first stationary engine around 1827; in 1838 he had 20 stationary and 4 boat engines in operation. Now well known as a machinist and engine maker, he was asked to build a working model locomotive for Franklin Peale's museum in Philadelphia, something that surely would attract customers. Success set Baldwin upon a path that would lead him to become the preeminent nineteenth-century locomotive producer. In basing invention on interactions on and off the job, Baldwin exemplified many successful machinists, who, like engineers and chemists, regularly studied technical advances as part of their occupational activities.[52]

Like Baldwin, those without college or engineering education found greater chances for success when their occupational knowledge was an advantage and their educational limits were minimized. As a result, the content of invention varied with the kinds of knowledge held by inventors. The relation between types of inventions and the source of learning illuminates the link. Table 6.6 divides inventors into four groups by their source of learning: college-educated and engineers, and, among those without such training, mechanicians from any occupation, mechanical occupations who were not mechanicians, and other nonmechanicians. The index of inventive incidence measures each group's share of each type of innovation relative to its share in all innovations. It thus expresses the specialization of inventive content for each source of learning. As the index rises, a group of inventors concentrated more on that type of invention; an index of 2 indicates twice the average concentration on an invention type.

Although each group patented in virtually every invention type, they did specialize. The college-educated and engineers used scientific knowledge especially in construction, electricity, chemistry, and steam engineering (listed by descending degrees of specialization in the first column). In construction they were unique. Led by bridge engineers, they were the only group with an index over 1. In a second set of inventions the college-educated and engineers shared leadership with other mechanicians (see the bold figures down the diagonal). Collegians and engineers had somewhat greater specialization in electrical, chemical, and steam and waterpower innovations, perhaps reflecting the importance of scientific mastery in these areas. Engineers and mechanicians without college education

Table 6.6. Major Innovations by Type of Learning: Indices of Inventive Incidence

Major innovation	College and Engineering	Mechanician	Mechanical	Other
Construction	**2.28**	0.40	0.72	0
Electricity and chemistry	**1.82**	**1.34**	0.36	0.42
Power, steam, and water	**1.71**	**1.27**	0.67	0
Transportation	**1.30**	**1.29**	0.62	0.90
Instruments and mechanisms	0.88	**1.22**	**1.20**	0.47
Metalworking	0.65	**1.80**	**1.01**	0.54
Agriculture	0.73	0	**1.43**	**1.91**
Crafts	0.26	0.55	**1.10**	**2.83**
Textile and apparel	0.19	0.40	**1.67**	**1.86**

Sources: See table 6.2.

Note: For groupings of major innovations, see table 4.10. The index of inventive incidence is the share for any group of inventors within any patent category divided by their share of all inventors. An index of 1.0 implies that their share in a category equals their overall share while an index above 1.0 that they concentrated invention in this category.

were heavily involved in railroad and navigation transportation. Among such innovation groups the college-educated and engineers had advantages based upon their scientific training and occupations, but mechanicians found other routes to gain propositional knowledge. In some cases mechanicians' inventions complemented those of the college-educated, such as the manufacturing techniques of Ezra Cornell and George Wilson that brought the scientific products of Samuel Morse and Eben Horsford to fruition.

In other types of invention those without education in colleges or engineering professions formed higher shares of inventors. A combination of mechanicians and mechanical occupations led a third set, consisting of instruments, mechanisms, and metalworking, in which much learning occurred on the job. Mechanicians outside engineers and the college-educated often shaped metal or made clocks, locks, firearms, and other mechanisms. In these sectors mechanicians' learning complemented that of practitioners, perhaps supplying elements that could not be learned within the occupation. The propositional knowledge that led to invention may have been concentrated in and transmitted through the practice of mechanical occupations. If this was so, the knowledge of mechanicians could be gained within the occupation; mechanicians could bring new knowledge to an occupation that was then transmitted within it. In this regard machinists and others working with mechanisms were like engineers and scientists.

Inventors who were neither college trained, engineers, nor mechanicians specialized in a fourth set of innovations that rested more on industry-specific knowledge, including agriculture, crafts, textiles, and apparel. New machines to print, harvest, spin, weave, and sew relied heavily on knowledge particular to the industries. Technological change had a strong cumulative quality within industries as inventors developed products that overcame limits to earlier techniques. The particularity of the technologies imposed access costs to those outside them. Knowledge was often embedded within tight networks. In printing a few press firms in major cities competed for large urban and town markets; communication and patent purchase tied such firms together. Textile inventors were overwhelmingly from Massachusetts and Rhode Island, where firms made complex machinery and their workers were regionally mobile. Agricultural innovation was the most dispersed; inventors were spread throughout the Midwest and western New York. It was the only sector in which most innovators were not urban. Yet agricultural machinery producers knew each other and monitored and in some cases licensed one another's patents. Although these sectors had the fewest recorded mechanicians, innovators possessed considerable mechanical sophistication in printing and textiles, though less in agriculture.[53] As these cases suggest, technological knowledge useful for invention existed even when mechanicians were few.

Because propositional knowledge applied to all natural phenomena, one might expect that mechanicians would play particularly important roles in major new types of innovation, which involved the biggest break with existing techniques. New innovation types can be approximated by sectors with four-fifths of innovators after 1835, including construction, electricity, chemicals, railroads, machine tools, measuring devices, sewing machines, shoemaking, rubber, and food processing. Electrical, chemical, and civil engineering improvements were dominated by mechanicians, who made up 80 percent of innovators, with 57 percent by engineers and collegians. The railroad was more evenly divided, with mechanicians making up 65 percent of innovators. Mechanicians constituted over half of the instrument and metalworking innovators. Yet 86 percent of apparel innovations, ranging from sewing machines to shoe machines to rubber fabrics, came from outside mechanicians or collegians.[54] The same groups dominated most craft and agricultural invention. Mechanicians were essential in developing basic new techniques in some sectors but not in others; no straightforward movement to more science-based technologies existed in the antebellum period. The learning patterns that fostered development within some innovation types also spread knowledge to related types.

Science and Ongoing Technological Change

Science clearly affected antebellum invention, as even the narrow criterion of whether scientific knowledge acquired off the job shaped inventive outcomes demonstrates. Scientifically trained practitioners—or mechanicians, as they have been called—arose when individuals found, at acceptable costs, scientific and mathematical knowledge that helped solve technological problems. About half of major antebellum innovators qualified as mechanicians. They utilized pure science, applied science, mathematics, and mechanical drawing across a wide range of inventions. Although pure science, especially at its frontiers, was only needed in exceptional cases, invention was not unguided trial and error because applied science contained the most widely usable aspects of propositional knowledge.

Arguably, those with the knowledge of mechanicians were far more numerous, for many industries and occupations had networks that spread quite sophisticated knowledge far and wide. Not waiting for outside infusions, many inventors created knowledge on their own, such as Perkins's steel-hardening techniques, Asa Arnold's differential gear, and the turbine inventions of Ohio millwrights. But then did practitioners have to be educated outside their occupations?

Many individuals successfully innovated without much technical education outside their occupation. Perkins and his visitors surely transmitted propositional knowledge, but much of the knowledge was gained on the job. The experience of such mechanicians suggests that science did not revolutionize production from on high. Yet one could hardly maintain that science, understood to encompass all propositional knowledge, was dispensable for all but industries grounded in pure science. First, to say that each individual need not have learned from outside the occupation does not imply that no individual needed such learning, for outside learning often was incorporated into the internal training of the occupation, including the design of engines, ships, and gears and the use of measurement devices and drawing procedures. Second, invention by the less educated was often limited. The Ohio millwrights who studied the *Young Mill-Wright* and the *Science of Mechanics* were hardly "empirical" when they developed their turbines. But lacking theoretical underpinnings, their experiments were not as effective as the more systematic inventions in Lowell.[55] Finally, the choice between learning on the job and off may have been, or have become, a false one. For leading practitioners in many occupations, machinists as well as engineers, consulted texts and experts as part of their work and sought employees with scientific knowledge.

The importance of off-the-job learning implies that extraeconomic institutions were essential to economic growth. From early on, they transferred Eu-

ropean applied science, compensating for U.S. backwardness. Evans sought European texts. Immigrating civil engineers and Americans studying abroad advanced U.S. development. Americans formed their own knowledge-transmitting institutions, emulating yet modifying European colleges, professions, government agencies, civil organizations, and publications. Once in existence, knowledge could be and was transmitted through occupations. Clock makers internalized mathematicians' gear-cutting formulas, measuring devices, and dividing equipment, and engineers spread knowledge of measurement, momentum, and structures. Science helped originate knowledge that was then transmitted and developed through economic mechanisms.

Science was not a crutch to be abandoned when the patient became stronger. Scientific institutions played an ever-growing role. The advance of science was one reason, but probably more important was its broader dissemination, organized in science-based education in high schools and colleges, a scientific press, scientific civil organizations, and applied science occupations. Governments contributed through public education and research as well as education and applications at West Point, the Ordnance Department, the Naval Engineer Corps, the Coastal Survey, and the army's Corps of Engineers. Like the machinery sector, organizations that developed and spread scientific knowledge constituted a technological center. Science did not have the same coherence as the machinery sector, which was structured by an industry and an occupation. Pure science had its own purposes, organization, societies, and professions. Applied science had different goals and organization, as did government bodies, educational organizations, the press, and mechanics' institutes. Yet each institution enhanced the availability of science, reduced the costs of accessing it, and eased its application to technological changes occurring in many industries. To be sure, innovation relying on advanced science was concentrated in some sectors, but the full range of off-the-job technological learning applied to many more sectors, including some that were the most "empirical." Moreover, scientific organizations and their products were linked to new occupations, including engineers, chemists, and electricians, and mediated others that increasingly relied on scientific texts and consultants.

The emerging complementarity of learning on and off the job worked in both directions. To understand the development and use of propositional knowledge, one cannot focus solely on science and the institutions transmitting it, however broadly conceived. For occupations applied that knowledge, and they developed new knowledge and posed new problems. Inventions such as the differential gear and problems such as steam engine efficiency in turn stimulated scientific inves-

tigation. Innovators themselves contributed to propositional knowledge, spread through lectures and publications. Among major innovators 92 percent of professors, 28 percent of other collegians and engineers, and 25 percent of all mechanicians published scientific and technological books and articles. Some advanced pure science, more wrote general tracts in mechanics and chemistry, and most depicted methods of civil engineering, engine making, ordnance, and many other technologies. Innovators were hardly the most important scientific investigators, but they contributed to the feedback from technology to science, which in turn expanded knowledge that supported technological advances. As Mokyr maintained, feedbacks between the development and application of propositional knowledge mapped out a path of ongoing technological change. By 1860 that path had been well established in the United States.

Wider invention was one outcome, a kind of "democratization of invention," as Kenneth L. Sokoloff and B. Zorina Khan termed it, grounded in the activities of leading occupations. But the democratization could not have occurred, at least with anything like the force it acquired, without the development of propositional knowledge from outside the crafts. Such learning from above, often linked to learning from abroad, came to be interfused with occupational knowledge and transmitted through occupational networks. Moreover, development from below acquired its own structure; private activity utilized interindustry technological convergences to propel changes affecting many industries. Machinists and applied scientists were central agents of change. A powerful economic dynamic had formed, linking a growing number of industries within a positive feedback system. But the economic dynamic was ever more structured by outside sources of knowledge, modes of learning, and ways to appropriate returns. Science, economy, and polity had come together to invent, secure rights in inventions, and utilize inventions to change products, production, and productivity.

The Patent System and the Inventive Community

American support for invention was so strong that little debate was needed to include a patent provision in the Constitution. Shortly after ratification, the Patent Act of 1790 formed rights to intellectual property in inventions and copyrights. The act and its successors aimed to spur invention by strengthening incentives and by spreading new technological knowledge. Patenting would solve two problems that might limit a purely private system: how to make knowledge of new techniques public when it could have been held in secret; and how to secure returns to inventors even if new knowledge was widely shared. The combination of public knowledge and private incentives was expected to foster invention.

Whether the patent system stimulated invention was often questioned. Many inventions went unpatented. To Oliver Evans the system offered insufficient support for inventors, who received nothing like the remuneration they deserved. Nor did it make knowledge available to even seasoned inventors; Evans had been forced to start at the beginning in each of his efforts, "often going over ground that others had exhausted and abandoned, leaving no record." He thought the government could overcome these limits. To strengthen rights, it could lengthen patents, extend the breadth of patent claims, and punish infringers. To make knowledge public, it could form "a Mechanical Bureau that should collect and publish all new inventions, combined with reliable treatises on sound mechanical principles."[1] By combining frontier knowledge with an exposition of known principles, the bureau would locate technical advances in a conceptual system. Inventors could study past efforts, learn from past mistakes, and invent more effectively. Because inventions relied on common scientific and mathematical concepts and procedures, inventors could apply principles in one invention to many problems. To this end the bureau could classify inventions in a way that their core technical principles could be accessible to inventors targeting quite different uses and thereby promote efficient searches to solve technical problems. Such a bu-

reau could convene a group of scientifically trained examiners to ensure that each invention was novel and useful. The public would thus identify "true" inventions and avoid studying old techniques masquerading as novel.[2] Put in more modern terms, the government could make knowledge more public and reduce transaction costs around its acquisition.

By 1860 the patent system gained some of the characteristics Evans sought but had few when the Patent Act became law. By the 1840s Patent Office standards and procedures, markets for patent rights, activities of patent agents, and publications had structured a community of inventors spanning much of the economy. Civil organizations and industrial fairs added to the structure. In the context of advancing industrialization, the evolution of the patent system greatly extended patenting and patent usage. The system's effectiveness grew from the mid-1830s, when patent law changed fundamentally and scientific occupations came to administer it. The restructured Patent Office changed patenting incentives and modes of diffusion, addressing Evans's concerns about insufficient rewards for patenting. Governmental and civil organizations formed novel means to spread technological knowledge, thus realizing some parts of the Mechanical Bureau. The development of invention thus rested on economic and scientific institutions but also on patent law, its administration, the institutions surrounding it, and wider civil organizations. The question is to figure out how such factors, separately or in combination, formed a context that deepened and spread innovation.

The Social System of Inventing

The 1790 act established the world's first examination system for conferring patent rights. Three examiners, no less than the secretary of state, the secretary of war, and the attorney general, judged whether the invention was novel and useful. The scope was worldwide; inventors had to originate a technique for all of humanity. Important disputes concerned the extent of originality; Jefferson, concerned about extending monopolies, insisted that inventions involve more than mere combinations of known principles. Questions about the requirements for novelty would continue through the century. Although he questioned its originality, Jefferson accepted—and licensed—Evans's flour-milling patent, the country's third.[3]

Partly because examining patents was so taxing, a 1793 act emulated England by establishing a registration system, in which applicants secured patents by completing a series of formal requirements, including providing specifications and drawings and paying a fee. A superintendent of patents and some clerks

administered the office. The patent system as a whole included courts, which decided whether patents were novel, useful, and used legally. Lawyers entered the system in suits over originality and, to an unknown extent, in drawing up specifications and reissuing and extending patents. By the mid-1820s the patent system included publications. Before 1825 the first superintendent of patents, William Thornton, tried to limit the spread of knowledge of patented improvements until the patent had expired. Peter Browne, a Philadelphia lawyer and Franklin Institute recording secretary, prompted the key change. Browne wanted to instruct mechanics in recent invention, but Thornton resisted his effort to acquire copies of patents. Browne successfully challenged this policy in 1825, and the *Journal of the Franklin Institute* published specifications and claims from the late 1820s, which were widely read.[4]

The Patent Act of 1836 reestablished an examination system. In the argument of Senator John Ruggles of Maine, who drafted the legislation, the old system allowed anyone to claim patents even for manifest copies, manufacturers were hit with false royalty charges, and true inventors had little advantage until litigation was complete. With the new legislation the government accepted responsibility for making judgments about an invention's novelty and utility, though still subject to judicial review.[5] The task fell to the Patent Office commissioner and examining clerks. A complete application involved six steps: submitting a petition; taking a legally recognized oath claiming novelty; providing a patent specification describing the invention and its claims to novelty understandable by one trained in the relevant occupation; presenting drawings; furnishing a model in most cases; and paying a $30 fee. When these conditions were met, the examiner searched all records, including patents in the United States and elsewhere, U.S. caveats (placeholders for future patents submitted to the Patent Office describing inventions in the making), U.S. and foreign publications, and evidence about actual usage.[6] The examiner rejected the patent if its claims were not novel, if the description was insufficiently precise or inconsistent with the drawings or model, or if the invention could not function as described or was not useful. The applicant could then revise and resubmit the specification. The patent commissioner administered the office and represented it publicly. A machinist maintained and repaired models, draftsmen copied drawings and restored drawings after the 1836 Patent Office fire, and clerks recorded submissions, patents, caveats, assignments, and payments.

Examiners had great power because their judgment, only exceptionally questioned by the commissioner, provided prima facie evidence of novelty, which was rarely overturned by the courts. Much hinged on their appointment. Senator Ruggles noted several qualifications: "extensive scientific attainment, and a

general knowledge of the arts, manufactures, and the mechanism used in every branch of business in which improvements are sought to be patented, and of the principles embraced in ten thousand inventions patented in the United States, and of the thirty thousand patented in Europe." On top of these qualities, examiners needed knowledge of law and judicial decisions.[7] The first examiner was Charles Keller, who had worked at the Patent Office, had provided informal judgments about novelty in the registration system, and had advocated effectively for new patent laws. Later examiners typically were trained in science. Thomas Jones, the second examiner appointed in 1837, had been a professor of mechanics and natural philosophy and the long-time editor of the *Journal of the Franklin Institute.* The first five examiners included the eminent physicist Charles Page and West Point's best mathematics and natural philosophy student, W.P.N. Fitzgerald. The next six examiners all were scientifically trained, including a chemist, a mathematician, a leading mathematical physicist, a naturalist, a military engineer, and a prominent Columbia-trained engineer. Other scientists followed in the early 1850s. The examiners made the Patent Office "truly remarkable for its concentration of scientific expertise."[8] Many joined scientific organizations. Patent examination became a possible career for scientists, one of the few in the country that provided adequate income. Scientists remained common in the examining corps until a reaction in the late 1850s.[9]

Scientifically trained examiners conceived inventions as applications of scientific principles and knew these principles and how to research their usage. Such knowledge often led to rejections on grounds of lack of novelty, misstated novelty, or lack of conformity among description, claims, and drawings. Unlike occupationally grounded inventors, examiners were concerned with novelty regardless of industrial use, and so they researched widely. As patent files indicate, redrafted specifications were common, including those of Matthias Baldwin and William Sellers.[10] When patent applications increased from 800 annually in the early 1840s to 6,000 around 1860, examiners did as well. Principal examiners numbered 1 in 1836, 2 in 1837, 4 in 1850, and 12 in 1858. By 1858, 14 assistant examiners added to the technical staff.

Skills to invent and to patent often diverged, and a number of occupations arose to bridge the gap. Most important, the patent agent tried to write specifications that accurately and fully grasped the novel features of the invention in order to secure the broadest rights for the inventor. The agent had to make the specification, drawings, and model consistent, work with examiners, and perhaps redraft the specification. William P. Elliot advertised his services accordingly: "Procures Letters Patents in the United States and in Foreign Countries, and gives advice on questions relating to Patents and Inventions; makes examinations at the Pat-

ent Office, has Models, Drawings, Specifications, etc. prepared from sketches and descriptions transmitted through the mail."[11] Successful agents required substantial knowledge of past patents and techniques in use, entailing the same research that patent examiners undertook. Strong specifications incorporated the widest allowable claims in terms understandable by examiners and skilled producers. Agents needed access to the Patent Office to examine patents and models and interact with examiners.[12]

Patent agents multiplied after 1836. Among the first was Thomas Jones, who gained detailed knowledge of patents from his long-running "Inventions" section in the *Journal of the Franklin Institute*. William P. Elliot left the Patent Office to become an agent. They dominated the market in the late 1830s, together writing 163 patents in 1839 and 1840, one-fifth of the total. At least five other agents operated by 1840. Many leading inventors used their services; Jones's clients included Isaac Babbitt, Samuel Colt, Charles Goodyear, and Henry Worthington.[13]

As patent applications skyrocketed after 1843, patent agents grew commensurately. By 1850 five cities listed 27 agencies in their directories, and because some city directories did not list patent agents, the actual number was larger (table 7.1). With its proximity to the Patent Office, Washington, D.C., led with 9 agencies (not including the Washington offices of agencies located elsewhere). Agencies grew greatly over the 1850s. Seventeen cities listed 116 agencies around 1860. Washington, D.C., led with 43, followed by New York's 20 and Boston's 14. Agencies outside Washington had branches or subagents in that city, clustered around the Patent Office. Agents were widely distributed in all regions except the South.

Agents charged from $25 to $50, commonly exceeding the $30 patent fee. The increased chance of receiving a patent and its superior quality and enforceability often warranted the charge. According to one patent examiner in 1850, a slight majority of patentees used agents; later the share rose.[14] Advertisements highlighted the benefits. In 1850 Watson and Renwick emphasized their "long experience as Practical Mechanics, added to a thorough knowledge of the Patent Laws, and acquaintance with the details connected to the business of the Patent Office." From their Washington, D.C., office, they could "make the proper searches in the records and among the models of the Patent Office and in the library provided for the Examiners." Aza Arnold, a leading textile inventor, singled out his specialized knowledge: "His experience as well as his scientific knowledge, and his intimate acquaintance with the mechanical operations, enables him to understand new inventions, to distinguish them from those already patented, and to specify them with facility and accuracy." Others emphasized Patent Office employment; in 1855 the Boston agent Samuel Cooper advertised that he had been the chief

Table 7.1. Patent Agents and Patent Agencies, 1848–1862

	Agencies, 1848–53	Cities with Agencies, 1848–53	Agencies, 1858–62	Cities with Agencies, 1858–62	Agents, 1836–62
New England	4	1	19	4	27
Mid-Atlantic	22	3	74	7	111
West	1	1	23	6	35
South	0	0	0	0	0
Total	27	5	116	17	173

Note: Agencies and agents were determined from listings in city and business directories. Directories understate the actual number because some were not listed as agents or listings had not yet been established. Agencies were counted with their principal city if they had more than one office (often a branch in Washington, D.C.). A few other agencies operated in the 1854–1857 years. The Middle States includes Washington, D.C., which had about one-half of the regional total; its agencies may have been overcounted if some functioned as subagents.

examiner and included endorsements from eight principal and assistant examiners, suggesting good treatment for his clients.[15]

In spite of rapid entry and the custom nature of production, one firm, the Scientific American Patent Agency, dominated the field. It wrote from one-quarter to one-third of all patents by the late 1850s and a larger share of patents issued through agents. One critical reason was the national reputation of its affiliate, the *Scientific American,* through which it advertised and gained the trust of inventors. Other agencies had their own journals, including the *Inventor, American Polytechnic Journal,* and, late in the period, the *American Artisan* and San Francisco's *Mining and Scientific Press.* Many agents were recommended by patent commissioners, patent examiners, or prominent clients, but no other agency garnered more than a small percentage of the market.[16]

New occupations made patent drawings and models. Urban craftsmen got some drafting training in mechanics' institutes, but few could make patent-quality drawings. The Scientific American Patent Agency attributed its origin partly to inquiries from inventors about mechanical drawing services. City directories listed three dozen professional draftsmen around 1860, and many patent agents integrated into drafting. Drafting also was essential for infrastructural projects and to design buildings, boats, locomotives, and, increasingly, engines and machine tools.[17] Model making used conceptual, metalworking, and woodworking skills to plan and construct working models of inventions. Machinists often held these skills, including those the Patent Office employed to maintain its models, but most others did not. About 70 model makers (often grouped with pattern makers) listed services in directories for nine cities by 1861; others doubled as

machinists. With an eye on patent applicants, in 1860 one New York City model maker advertised "small machinery and models on scientific principles. References editor Scientific American." Model makers found wider markets. In 1861 one Boston model builder advertised as "mechanical draughtsman and patternmaker. Models made for the Patent Office; Patterns made for Machinery; Steam and Gas Fittings; Moulds and Patterns for Stone-Cutters."[18]

Patenting professions continued their work after the patent was issued. Patent agents often wrote contracts to assign or license patent rights. Occasionally, they bought and sold rights. David Hinman assigned one-third of a steam piston patent to his agents, Charles Keller and John J. Greenough, with the provision that "said K&G agree to defray the expenses in putting up a machine to test the said invention, also to give their effort and personal attendance to sell and introduce the same to the public. Hinman . . . assigns them one third part of all the net proceeds arising from the sale of said invention . . . Hinman further agrees to make them his sales agent for the sale of the invention."[19] But many agents accepted the Scientific American Patent Agency's view that selling rights might introduce conflicts of interest with patent applicants.[20] A few people specialized in buying and selling patent rights, listed in directories as patent dealers. Patent agents helped reissue and extend patents. Many agents doubled as patent attorneys, who sued for infringement or defended inventors from others' suits. Patent suits rose dramatically in the late 1840s and 1850s, roughly in proportion to the number of patents.[21] Patent experts used extensive knowledge of technology, often gained in scientific work in colleges, to testify in such suits.

Civil organizations, the Patent Office, and private journals published descriptions of inventions. The patent commissioner's annual reports published only a list of patent titles and patentees until 1843, when they included patents' claims to novelty. Somewhat earlier they published examiners' reports of patenting developments, together with the commissioner's remarks about (inadequate) personnel, buildings, and financing. Soon after its inception, the *Scientific American* published names of patentees, patent titles, and patent claims on a weekly basis and highlighted some patents in longer articles, particularly those its agency handled. In 1853 information improved when the *American Polytechnic Journal,* issued by the patent agency of Charles Page, J. J. Greenough, and C. L. Fleischmann, printed illustrations in addition to short descriptions and lists of patent claims. It stopped publication in 1854, in part because the Patent Office had begun incorporating fuller, illustrated descriptions in its annual report. After 1850 technical dictionaries and other books highlighted European and U.S. patented and unpatented inventions.

The Patent Office, patent agents, model builders, draftsmen, engineers, publishers, and civil organizations structured a loose-knit inventive community. A complex intersection of law and its administration, scientific communities, civil organizations, and private services of agents, model makers, and publishers organized the community. Patent agents and examiners had the most in common because both assessed the novelty of patents using the same sources. There was substantial mobility between them, beginning with Thomas Jones and William Elliot. Of 39 Patent Office employees through 1853 whose jobs required extensive technical knowledge (including examiners, commissioners, draftsmen, and machinists), 19 had become patent agents or attorneys by 1861.[22] The Scientific American Patent Agency advertised that it employed past examiners and a former commissioner. At least one examiner became an agent and then returned to examining. Such cross-fertilization helped establish standards for novelty and the language and form of patents, which integrated patenting into broader scientific communication. Individuals often played more than one role. Half of the 1855 Boston agents also advertised as civil, mechanical, or consulting engineers. One agent, who had been a patent examiner, doubled as a chemist. Other agents were patent attorneys or published technical journals. Standing examiners could not be patent agents or take out patents, but many published scientific experiments and advised patentees, including Charles Page, whose efforts improved Samuel Morse's telegraph.[23]

Although national in scope, the community centered around Washington, D.C., and the Patent Office. It linked inventive occupations to prominent inventors, whom agents and examiners knew, and to the scientific community, which generated many examiners, agents, and engineers and retained ties to patenting through lectures, mechanics' associations, science publications, and testimony in patent cases. Civil organizations connected scientists with inventors, examiners, agents, exhibition attendees, and journal readers around the diffusion of domestic and foreign technological knowledge. They integrated wide ranges of people, as involvement in industrial exhibitions suggests. Among 220 foreign and domestic officers and jury members of the 1853 New York Crystal Palace Exhibition, the 124 Americans with known occupations included 5 farmers, 8 machinists, 25 manufacturers, 42 merchants, lawyers, military personnel, and other trade and service occupations, and 44 engineers, professors, chemists, and other scientific workers. Nearly half were listed in biographical dictionaries, half of them possessing a college education. Their activities linked thousands of exhibitors to hundreds of thousands of customers.[24]

The inventive community would persist in substantially the same form throughout the century.[25] Through its mediation much private knowledge be-

came public. Most groups at the core of the inventive community did not aim at inventing per se but, rather, at achieving and employing property rights for inventions or at judging and spreading knowledge about inventions. Whether they fostered invention, and not merely its legal recognition, remains to be seen.

Patent Incentives and Usage

The patent system and invention-supporting institutions could have contributed to invention by increasing inventors' returns or advancing their knowledge. Incentives to invent were greater when the exclusive right to use or sell an invention gave it more value than simply being able to use it.[26] Knowledge of patents could have directed attention to inventive problems and provided solutions. Such effects on incentives and learning grew as that system expanded and evolved.

Inventors could have and did appropriate returns to unpatented inventions through secrecy or complementary knowledge of design and production; Evans argued he only benefited from his engine patent when he concentrated on manufacturing.[27] Patents added to returns by the obstacles they set up and the obstacles they overcame. With exclusive rights, inventors might prevent usage by others and monopolize usage within their own firms. This obstacle was valuable to the extent that courts enforced the patent, infringers could be monitored, and inventors' firms could profit. The patent also overcame obstacles to inventors, who could assign or license the invention if they lacked the capabilities to use it. Both obstacles would operate when inventors used inventions in local markets or for their own products and assigned in other areas and uses.

The patent system supplied increasingly clear, enforceable rights. Early in the period limited knowledge of techniques and patents made it difficult for inventors to discover whether inventions were new. David Wilkinson's efforts illustrate the problem. To discover the originality of his lathe, he searched workshops in Connecticut, New York, and Philadelphia and learned of another in Delaware. He enjoyed the search, but it was costly.[28] From the 1820s published patent claims reduced the uncertainty, as did patent agents. The examination system provided earlier knowledge of enforceability. Patent rights had little importance if the courts did not enforce them. Relatively few patents were litigated; the best study unearthed 795 cases litigated in federal courts through 1860, a tiny share of the 41,000 patents issued during that period. The share of patents litigated is even smaller because most cases concerned a few major patents. Judgments broadly upheld the rights of patentees, providing some confidence that patents were enforceable.[29]

Inventors sold patent rights extensively. Licensing is difficult to trace, but assignment was common after 1836, when assignment records first provided systematic data. Researched patentees in the all-inventor sample had more assignments than patents, led by two inventors of clothes dryers and plows, with 55 and 51 assignments, respectively. Others had hundreds of assignments, including Thomas Blanchard and Charles Goodyear. Three-eighths of the all-inventor sample assigned at least one patent outside their firms and families (see table 4.14). Machinists had the highest shares assigning, but occupational groups other than farmers had only modestly lower shares. Nor did assignment create a group of professional inventors; only four patentees—0.5 percent of inventors with known occupations—listed their occupations as inventors, and two quickly found other occupations. The share of inventors who assigned patents was so high because patents had perceived value, inventors found assignment in their interest, and inventors were able to locate assignees. In the words of Naomi Lamoreaux and Kenneth Sokoloff, a market for technology had originated.[30]

For many inventors assignments were a major source of income. The most famous was Thomas Blanchard, whose 1819 pattern lathe patent, with renewals, ran for 42 years. Blanchard assigned patents to locations in New England and New York by 1840 and throughout the Midwest, as far south as Arkansas, and as far west as Nebraska by 1860. Over time assignees widened the range of usage to include gunstocks, tool handles, spokes, and carriage parts.[31]

Some inventors targeted the assignment market. Dexter H. Chamberlain owned a small Boston machine shop, where he invented widely. His 30 patents included harpoons, awls, tools, compasses, faucets, pistols, sawmills, curtain fixtures, purifying gas, lamps, printing presses, leather splitters, and hot-air engines, together spanning a remarkable 14 of 34 patent categories. His 82 assignments covered 26 inventions. He sold full or partial rights and kept an interest in several assigned patents. Chamberlain found a wide array of purchasers, including 6 at the time of issuance and 23 later. His location and reputation linked him to assignees for very different kinds of patents. That 27 assignments occurred within one year of issuance suggests he had lined up customers before patenting. His patent agent, Samuel Cooper, arranged one assignment. Unlike many patentees Chamberlain did not assign a power of attorney for any of his patents. Secondary markets (in which assignees sold their rights) arose in six distinct types of patents; the most prominent involved 25 transfers of gas-purifying implements. Several secondary assignments involved rights for counties and other territorial units.[32]

Very few patentees matched Chamberlain's breadth of invention and assignment. Assignors usually concentrated on one or two patent types. Joel Wisner had

Table 7.2. Assignments by First Year of Patenting

	Pre-1836	1836–40	1841–45	1846–50	1851–55	1856–60	All
Number	22	39	41	40	55	104	301
Any assignment (%)	71.9	49.4	55.8	50.9	46.0	34.9	43.5
Assigned to others (%)	71.9	49.4	54.6	48.4	40.2	26.9	38.2
Territorial assignment (%)	50.8	31.8	27.9	27.6	23.9	9.2	19.5
Nonterritorial assignment to others (%)	40.2	24.5	34.2	31.1	33.8	20.4	26.4
Average patents	5.03	1.95	2.41	2.09	2.55	1.60	2.09
Assignments to others	4.83	2.25	2.73	2.42	3.11	2.19	2.70
No assignments to others	5.53	1.66	2.02	1.77	2.17	1.39	1.70

Source: U.S. Patent Office, "Patent Assignment Digests," National Archives, College Park, Md.

189 assignments for four washing machines and one other patent, overwhelmingly secondary assignments for territories down to the level of counties. In the all-inventor sample over half who assigned patents had only one or two assignments. That even minor inventors could secure returns from patenting suggests that inventive effort was not misplaced.

Assignments were common throughout the period. When inventors are grouped by the year of their first patent, the share with any assignments remained about 45 percent through much of the period (table 7.2). The higher share for the pre-1836 cohort than the 1856–60 cohort reflected their higher number of patents and longer period to assign them.[33] For the two-fifths of inventors who assigned patents to others, sale was a form of diffusion. This share fell modestly over the period, perhaps manifesting growing usage by patentees themselves.

Territorial assignment declined over time. Over the whole period one-fifth of inventors recorded a territorial assignment, and because only a few assignments were sampled for each inventor, the actual share was higher. Half of the earliest cohort of patentees assigned patents for regions, states, and counties. The share declined steadily to one-tenth for patents after 1855.[34] Over time assignees increasingly sought control for the whole country, a trend that would continue throughout the century. A principal reason was the rise of national markets.[35] Similarly, territorial assignment among machinery principals concentrated in agriculture, woodworking, and sewing machines but not locomotives, printing presses, or other sectors with national markets (see table 5.6). Sewing machines marked a transition; early inventors assigned territorially, but later inventors did not. Likewise, in early-industrializing sectors woodworking inventors assigned the most territorially, reflecting the local character of many such markets, while inventors of printing presses, clocks, and textile machines had little territorial assignment.

Table 7.3. Patent Assignment by Region and City

	New England	Mid-Atlantic	South	West	All	Cities	Towns and Rural
Inventors	85	153	15	48	301	156	145
Any assignment (%)	50.2	45.7	46.5	28.2	43.5	53.9	35.2
Assignment to others (%)	41.4	40.7	46.5	25.4	38.2	49.8	28.9
Territorial assignment (%)	19.4	19.3	21.1	19.6	19.5	18.0	20.7

Source: See table 7.2.

Assignment might have had particular benefits for inventors outside major manufacturing areas. Assignment occurred everywhere; over a quarter of inventors assigned patents in every region and inside and outside cities (table 7.3). The share was somewhat higher in the industrialized East and in cities, perhaps because information flowed more readily. Assignments did benefit inventors where manufacturing was thin. Territorial assignments made up a greater share of assignments outside cities and in the West, providing an avenue for inventors outside manufacturing centers to benefit from the patent system.[36]

An effective market for patent rights had to match patentees with assignees. For potential purchasers assessing the value of a patent was costly and uncertain. Purchasing territorial rights provided better information if the patent had been successfully used elsewhere, but the first purchaser faced the same problem: what supplied knowledge in the market for technology? Industry practitioners and their capital goods suppliers spread knowledge through industry communications networks. In early-industrializing sectors 54 percent of network inventors assigned patents to others, and 43 percent assigned internal patents (table 7.4). Network inventors had better access to potential users, lower transactions costs, and perhaps greater trust. Network inventors also gained use in their own firms, so that nine-tenths of them secured at least potential usage because they assigned internal patents or ran firms that could use the patents.

Inventors outside networks had to find other mechanisms. Such inventors actually assigned a modestly higher share of internal patents than did network inventors, though the shares varied by industry. Industrial exhibitions, models, prototypes, trials, personal contacts, and fast talking all spread knowledge. Journals advertised patents nationally, especially the *Scientific American;* its feature articles often offered to sell patent rights. In its words, "The means which are at the command of inventors at the present day—such as the press—to disseminate a correct knowledge of their improvements throughout the civilized globe, are such as no previous age in the world's history could boast of."[37] An 1854 issue of

Table 7.4. Assignment and Usage by Urban Inventors in Early-Industrializing Sectors (percentages)

	Textiles	Steam Engines	Printing Presses	Clocks	Wood-working	Firearms	All
Urban inventors	13	16	36	21	34	20	140
Networked share	53.8	37.5	55.6	76.2	38.2	40.0	50.0
Networked							
Assignment to others	71.4	50.0	50.0	43.8	61.5	62.5	54.3
Internal to others	57.1	50.0	40.0	31.3	46.2	50.0	42.9
Territorial assignment	14.3	0	15.0	6.3	23.1	12.5	12.9
Internal territorial assignment	14.3	0	15.0	0	15.4	0	8.6
Internal with potential use	85.7	100.0	85.0	100.0	92.3	75.0	90.0
Others							
Assignment to others	66.7	60.0	81.3	40.0	66.7	66.7	67.1
Internal to others	33.3	30.0	62.5	40.0	52.4	41.7	47.1
Territorial assignment	16.7	40.0	25.0	20.0	28.6	25.0	27.1
Internal territorial assignment	0	20.0	6.3	20.0	19.0	0	11.4
Internal with potential use	50.0	50.0	68.8	60.0	71.4	41.7	60.0

Source: See table 7.2.

Note: Only urban inventors who had known occupations and were listed in city directories are included. The first row refers to numbers of inventors, all others to percentages of inventors in each column.

that journal advertised patent rights for gear cutters, stone-drilling machines, plows, resawing machines, saw-filing machines, rifles, planing machines, and white straw paper. Most offered territorial rights, in some cases from assignees willing to subdivide their rights.[38] Patent agents located potential users, mediated the transfer of property rights, and at times purchased patent rights.[39] Through such means many nonnetwork inventors assigned when they could not easily use patents in their own production processes. Network patentees still had a far larger share with potential use (90% to 60%), but for others assignment overcame some disadvantages.

The patent system could have led to repeat invention if patenting—and not merely invention—formed incentives or learning supporting inventive efforts. In early-industrializing sectors inventors who assigned internal patents to others averaged 4 internal patents, compared to 2.5 for other inventors (see table 3.2). Similarly in the all-inventor sample the 2.7 patents of those who assigned to others well exceeded the 1.7 of others. Perhaps more patents presented more opportunities for assignment, so that patenting led to assignment, not the other way around. One indicator of the causality is whether inventors who assigned their

first patent were more likely to continue patenting. In the all-inventor sample those assigning their first patent to others received 1.3 additional patents, compared to 0.8 patents for others. A higher share continued patenting (43% to 36%), and their 4.0 patents exceeded the 3.3 for others. Network patentees using but not assigning their first patent widened the repeat invention gap.[40]

Patenting and Other Modes of Appropriation

To study invention solely with patent data is too restrictive because many inventions were not patented. The 58 major innovators who did not patent through 1865 found other incentives, and patentees often left other inventions unpatented. Innovators got returns by assigning patents to others, by embodying innovations in new products, and by using innovations in their own production processes. Each mode was significant. Among all major innovators 37 percent assigned patents to others (though in some cases not for their key invention), 57 percent sold products embodying the innovation, and 44 percent used their own innovations (table 7.5). Very few innovators only assigned patents and hence did not rely solely on patenting to gain returns. The vast majority of innovators used their own inventions. Patent sale offered auxiliary income, and about one-third of major innovators did assign patents along with using them in-house. But for most of them the importance of patenting was to deter copying.[41] Inventors who did not secure patents relied heavily on self-usage. In many cases self-usage did not reveal the change to others so that secrecy could increase returns to innovation.

Modes of appropriation varied by innovation type. Assignment to others was relatively low and self-usage high in construction and transportation improvements, which reflected the role of civil engineering inventions used by railroads and canals. Telegraph firms used their own patents but also assigned to others. Innovators who did not patent concentrated disproportionately in these sectors. Nonpatenting metalworking innovators concentrated in firearms, with its shared technologies, and foundries that used improvements themselves.

That many major innovators did not patent highlights the issue of whether patent data, even when coupled with careful industry studies, present a biased view of innovation. As case studies show, many changes in machines, tools, materials, ways of utilizing inputs, and product design were not patented. To differentiate between patents and innovations, Petra Moser used data from industrial fairs. She showed that at the 1851 London Crystal Palace Exhibition only 11 percent of British exhibits and 16 percent of American exhibits were patented. The patenting rate varied among industries; it was highest in machinery and far lower

Table 7.5. Modes of Appropriation for Major Innovators

	All	Assigned to Others (%)	Product Sale (%)	Self-Usage (%)	Only Assigned (%)	Without Patents	No Patents, Product Sale (%)	No Patents, Self-Usage (%)
Construction	21	19.0	33.3	81.0	0	9	0	100.0
Electricity and chemistry	36	40.0	31.4	62.9	2.9	4	50.0	50.0
Power, steam and water	33	45.2	80.6	25.8	3.2	3	100.0	0
Transportation	55	24.5	41.5	64.2	3.8	18	27.8	83.3
Instruments and mechanisms	49	41.3	63.0	37.0	4.3	6	60.0	40.0
Metalworking	47	36.2	55.3	42.6	4.3	10	20.0	80.0
Agriculture	31	46.7	80.0	13.3	6.7	2	50.0	50.0
Crafts	28	35.7	71.4	28.6	3.6	2	50.0	50.0
Textile and apparel	40	43.6	64.1	35.9	2.6	4	50.0	50.0
All	340	37.0	57.3	43.6	3.6	58	33.3	70.2

Sources: See tables 4.6 and 7.2

Note: Percentages are row percentages. Percentages from the modes of appropriation sum to more than one when inventors used multiple modes. Ten innovators are excluded because information is insufficient. Four of these were science professors who may have made their inventions freely available to others. Assignment to others includes known licensing.

in chemicals, mining, textiles, and food processing. The share patented was higher for award-winning exhibits but even in machinery did not reach half. Over wide ranges of technologies, then, patents constituted a distinct subset of innovations and thus a study of patents misses many changes in technology.[42]

The New York Crystal Palace Exhibition of 1853 provides an opportunity to study such issues in the United States. The exhibition included 2,200 U.S. entries and an equal number from 20 foreign countries and territories. Exhibits were divided into 31 classes, copying the 1851 Great Exhibition classification. To examine whether the distribution of patents paralleled the distribution of exhibits, I concentrate on 274 American exhibitors of technologies for which I have examined U.S. patents, including early-industrializing sectors, machine tools, engineering improvements, and related sectors such as railroads and apparel. The technologies examined had high patenting shares in the 1851 exhibition, especially machinery.[43]

Three-fifths of Americans exhibited patented products (table 7.6). In every category except clock makers, at least two-fifths patented. The shares were highest among specialized machines to harvest, telegraph, sew, print, and work wood, along with firearms. Shares were lower for textile, engine, transportation, and

metalworking sectors and lowest for engineering operations in construction and clocks. About half the exhibitors were themselves patentees, and another tenth utilized patents of others. Others who licensed patents would increase the share of exhibitors holding patent rights. Exhibitors used others' patents in virtually all technology types but were proportionately highest in construction and telegraphs, in which self-usage by large firms was common, and in firearms, in which large firms often purchased patents.[44] Among the technologies studied, patenting and innovation (proxied by exhibits) substantially overlapped.

Did the distributions of patents and innovations vary geographically? If the two distributions differed, then the location of patents would not reflect the location of inventions. To examine the issue, I compared locations for 261 exhibitors (excluding agents, who often represented innovators in different areas) and about 1,700 patents issued from 1836 through 1855, which could have been exhibited in 1853 (allowing for a lag between exhibition and patent grant). Table 7.7 expresses the comparison as a ratio of exhibit shares to patent shares, so that ratios over 100 percent had relatively more exhibits than patents. New England, for example, had 59 percent of textile and apparel patents but only 48 percent of exhibits, 81 percent of its patent share. The comparison is most accurate where numbers were large; the South's ratios varied greatly because it had only 6 exhibitors in three surveyed categories.

Across all patent types innovation shares systematically exceeded patent shares in the Mid-Atlantic States and were below them in other regions. They were also greater than patent shares in New York State and in cities with more than 10,000 residents.[45] This does not imply relative concentration of innovators in the Mid-Atlantic States and in cities in general but, rather, a bias toward New York City, which had an average exhibitor share almost twice its patent share.[46] If inventors and exhibitors from that city were omitted, New England, Mid-Atlantic States, the West, and New York State would each have overall exhibitor shares within 10 percent of patent shares. Other cities were 23 percent higher in exhibitor share than inventor share. But the striking conclusion is that outside the exhibition's sponsor city, patents were distributed very much like exhibitors, probably reflecting networks linking patenting, commercialization, and exhibition.

That many exhibitors had no patents raises the question of incentives: why would innovators exhibit when patents did not protect their efforts? To answer the question, it will help to understand who the exhibitors were. Almost three-quarters described themselves as proprietors or manufacturers (see table 7.6). They typically made and sold the product; displays at industrial fairs were means to sell and advertise, especially if they won awards. Innovative proprietors were

Table 7.6. Patenting by New York Exhibitors, 1853

	Exhibitors	With Patents (%)	Exhibitor, Own Patent (%)	Proprietors (%)	Proprietors with Patents (%)	Proprietors, Own Patent (%)
Construction	10	50.0	30.0	50.0	20.0	0
Electricity	8	87.5	62.5	62.5	80.0	40.0
Power, steam and water	54	55.6	44.4	72.2	53.8	51.3
Transportation	58	51.7	43.1	56.9	66.7	57.6
Instruments: clocks	9	11.1	11.1	100.0	11.1	11.1
Instruments: firearms	16	75.0	50.0	75.0	91.7	58.3
Metalworking	10	40.0	40.0	50.0	40.0	40.0
Agriculture: harvesting	14	85.7	78.6	100.0	85.7	78.6
Craft: printing	20	70.0	65.0	80.0	68.8	62.5
Craft: woodworking	34	70.6	55.9	85.3	65.5	48.3
Textile and apparel	41	63.4	56.1	82.9	61.8	52.9
All	274	60.2	49.6	73.4	62.2	51.7

Sources: Official Catalogue of the New York Exhibition of the Industry of All Nations, 1853, 1st rev. ed. (New York: G. P. Putnam, 1853); C. R. Goodrich, ed., *Science and Mechanism: Illustrated by Examples in the New York Exhibition, 1853–4* (New York: G. P. Putnam, 1854); Horace Greeley, *Art and Industry as Represented in the Exhibition at the Crystal Palace, New York, 1853–4* (New York: Redfield, 1853); data on patent and patent assignment.

Note: Percentages are shares of exhibitors. Proprietor status was determined from exhibition reports and patent status from these reports, annual reports of the commissioner of patents, and manuscripts of assignment data.

Table 7.7. Geographic Distribution of Exhibits versus Patents (percentages)

Innovation Type	New England	Mid-Atlantic	South	West	New York State	Cities	New York City
Construction	116	98	0	180	108	174	54
Electricity	105	123	0	0	221	128	340
Power, steam and water	94	99	176	93	185	114	440
Transportation	90	108	47	100	191	118	427
Clocks	54	189	0	0	172	151	252
Firearms	101	104	293	0	93	128	98
Metalworking	104	105	0	0	76	101	113
Agriculture: harvesting	Undef.	105	0	148	104	161	74
Craft: printing	69	119	0	108	104	116	149
Craft: woodworking	82	124	0	111	159	127	263
Textile and apparel	81	107	0	361	142	114	187
Average	88	115	40	91	136	128	195
Average, no New York City	100	103	55	108	95	123	—

Sources: See table 7.6.

Note: The cells measure the share of exhibits of each type relative to the share of surveyed patents issued from 1836 through 1855. New England's ratio was undefined for harvesting because it had no patents. The last two rows are ratios of the simple average of innovation shares to the simple average of patent shares.

common, as among machinery principals; three-fifths of proprietors held patent rights, and over half were patentees.[47] Thirteen exhibitors described themselves as agents, who represented nonlocal manufacturers or inventors; half had patents, all but one the patents of others. Fourteen percent were listed as inventors, 74 percent of them with patents. Eight designers and 14 with no description (including both federal armories) completed the group.

Incentives to display varied with the character of the exhibitor. Proprietors and agents typically sought orders for products directly and indirectly by gaining a reputation. Both Corliss and the Lawrence Machine Shop advertised engines that ran the exhibition's machinery, Stuart Gwynne's pumps ran the central fountain, and Elisha Otis achieved notoriety when first demonstrating his safety elevator. Inventors tried to sell patent rights or form partnerships, and designers sought contracts for their services. Such benefits mostly obtained whether or not the exhibitor had patents; even inventors without patents could gain financing or set up firms.

Exhibitors without patents risked spreading techniques that others could freely use. Other factors could outweigh this concern. Many unpatented exhibits used knowledge already employed in production, for which patents had expired or had not existed, so knowledge was available outside the exhibits. Yet they did include—and trumpeted—incremental changes that added to the usefulness of their product, even if the changes were not novel enough to patent. Some products did not reveal the process by which they were produced. Many firms had complementary manufacturing and design skills and associated reputations that conferred advantages even if their invention was observed. Well-reputed designers displayed models of ships or bridges; their return came in construction contracts. For many exhibitors of unpatented clocks, engines, and woodworking machines, the benefits of publicity outweighed the costs of emulation.

Patents tracked innovations less well in techniques that were not often patented. In technologies that I surveyed, 30 percent of U.S. exhibits in the 1851 London Crystal Palace Exhibition were patented, but only 9 percent were in other classes.[48] Surveyed classes encompassed three-eighths of exhibits at the New York Exhibition.[49] Many other exhibits involved less new technological knowledge than potentially useful inputs or skillfully executed or stylishly designed products. Nearly a fifth of American exhibits consisted of samples of minerals, sugar, flour, tobacco, cotton, and wine. Examples of cloth and its products constituted another 15 percent. Neither group was widely patentable, though manufacturing processes (often classified with machinery) might have been. Manufactured products, which made up most of the other exhibits, fell in between; many were

consumer products known for their functionality, finish, and appearance, but some products and manufacturing processes were patentable. For many exhibitors the exposition was like a trade show, a means to advertise and sell products. Production skills, marketing capabilities, reputation, and hard-to-discern techniques protected them from successful emulation. Many used patented machinery, so that the geography of patents and of exhibits was similar. New England, for example, was home to 70 percent of cotton, woolen, mixed fabric, and printed and dyed textile exhibits and to two-thirds of textile machine patents. Its firms displaying "fine sheetings and shirtings," "all wool flannels," "cotton warp fancy cassimeres," and "fine printing on calicoes" rarely invented the machinery they used, but regional networks kept them in constant touch with inventors.[50]

Exhibitions make clear that innovation was linked with patents, but it also involved unpatented novelties, diffusion, widening invention, improvements in use, and product refinements. Patents mattered; most exhibits in some technologies were patented, others relied on knowledge that became public when patents expired, and seldom-patented exhibits often rested on patented techniques. Others used firm-specific knowledge and reputation to gain returns. Patentees did as well, which was reflected in the integration of invention with manufacturing. Like machinery principals, exhibitors were often both proprietors (or incipient proprietors) and inventors. Patentees and others were integrated into industry knowledge flows. Patenting added an incentive when inventors could not use the invention and to prevent others from doing so. As Moser argues, patent systems may have directed invention toward more readily patented technologies.[51]

As a result of factors outside and inside the patent system, barriers to invention declined as the period progressed. Economic expansion, rising incomes and wealth, and market integration all strengthened returns to patenting. Market integration clarified potential markets for patents and helped locate assignees and infringers. The U.S. patent system better supported patenting than did England's because procedures were simpler and the filing costs, though a considerable part of an annual wage, were far beneath England's fee of around $500. Lower fees increased patent filing for the same range of expected returns and might have fostered the willingness to invent when returns were uncertain. Americans benefited from the greater certainty of the examination system and the expansion of publications. Partly for such reasons, Americans patented more per capita than did the British almost from the beginning, which is striking because early British inventors enjoyed greater technological knowledge and Industrial Revolution opportunities. Patenting became easier, more secure, and more common.[52] Patenting and broader inventive institutions increased incentives to invent. As

Evans had hoped, they also helped overcome "the want of reliable knowledge of what had been done."[53]

Public Knowledge and Technological Learning

If the patent system effectively organized and communicated technological information, it could have fostered invention by spreading knowledge in addition to providing incentives. By adding to knowledge, past invention could help identify new technological problems and potential solutions, thereby reducing the cost and uncertainty of further invention. Such useful information grew with people's involvement in patent-related institutions, the completeness of the information they gained, and their capacity to absorb it.[54]

The patent system was one among many eighteenth- and nineteenth-century information systems. According to Daniel Headrick, information systems performed five functions. They gathered information, classified and organized it, displayed it in multiple usable forms, stored and retrieved it, and communicated it. Many systems performed one or two functions; scientific vocabularies organized information, statistics and pictures represented it, encyclopedias and dictionaries stored it, and newspapers and the mail spread it.[55] The patent system, understood as the institutions associated with the recognition of inventions as intellectual property, combined all the functions. It had a ready-made means to gather information with little effort by the Patent Office because inventors prepared descriptions of their own patents and paid fees to have them examined. Drawing on applied science, patents adopted a common language familiar to many. The accepted form of patents expressed novelty in a series of claims. Patent submission required that information be presented in varying forms, including written specifications, drawings, and models. The Patent Office kept information and made it available to the public, though an 1836 fire destroyed all specifications, drawings, and models. The Patent Office's annual reports and model room, together with private publications and exhibits, spread knowledge widely.

Learning began when inventors explored patentability. The Scientific American Patent Agency offered two forms of consultation. If inventors submitted an informal drawing and a description or a model, the agency commented at no charge. It communicated information in a "Correspondents" column in *Scientific American;* the dozen or more responses weekly praised some inventions but discouraged patenting when inventions were unoriginal or ineffective. The journal estimated that half of its comments discouraged efforts to patent.[56] The variety of comments gave inventors confidence in the objectivity of the journal and,

by extension, its agency. For five dollars the agency's Washington, D.C., branch conducted a patent search; of 1,500 investigations conducted in 1859, it recommended against patent application for almost half.[57]

Agencies often prepared specifications and drawings based on models and the inventor's rough drawing and description. Designing models might refine the invention, and in writing specifications agents clarified mechanical principles and described them with more powerful concepts than the inventor would have used. Learning from patent examiners was of the go–no go variety: was the invention novel or not? In 1851 the textile machinery producer James S. Brown applied to patent an engine lathe. The examiner questioned one claim on the basis of overlaps with Brunel's British block-making machinery. Brown responded, distinguishing his machine from Brunel's, Blanchard's pattern lathe, and two lesser machines. To his dismay, he received another rejection, now based on a machine depicted in Hebert's *Encyclopedia.* Brown protested again but to no avail; the disputed claim was deleted.[58]

Inventors learned about the novelty of their creations through such interactions, but patent agents, draftsmen, model builders, and patent examiners learned more: the core principles of the invention. Examiners and agents placed the invention in relation to the stock of inventions. Their research centered on the patent library, a locus of technological knowledge with a collection that grew from 1,850 volumes in 1847 to 5,750 in 1853 and 15,000 in 1865, in addition to patent specifications, drawings, and models. The *Scientific American* only modestly exaggerated when it wrote, "The library contains perhaps the most valuable collection of scientific works in the world."[59] When examiners and agents located the invention in relation to wide ranges of techniques, they perceived applications more broadly than the inventor recognized. Because they examined many patents—principal examiners reported annual loads in the hundreds and patent agents in the dozens and upward—they had ample opportunity for learning.[60]

Knowledge of the patent broadened after the patent was granted. The sale of invention-embodying products was a source of learning. To sell patent rights, the inventor often supplied complementary knowledge about the technique. Full patent specifications could be purchased or studied at the Patent Office. Publication spread knowledge more widely. The *Journal of the Franklin Institute* published patent claims with Thomas Jones's insightful commentary. Weekly issues of the *Scientific American* included recent patent claims, a few longer illustrated patent descriptions, some shorter descriptions, and discussions of broader issues in technology and science. The average circulation of 8,000 per issue in 1848 had tripled by 1859. Other journals circulated on smaller scales. The annual reports of

the commissioner of patents were widely read. In 1843 the 3,000 published copies included patent claims, principal examiners' reports of advances within their purview, and indexes of patents classified by name and type. From 1851 through the end of the decade about 60,000 copies were published annually, 10,000 of them used by the Patent Office. In 1853 the annual report added fuller descriptions and illustrations of patents.[61] Cumulative indexes of U.S. patents were published in 1839 and 1846. Descriptions of most foreign patents were also published but were not so readily accessible in the United States.

The content of such knowledge was nothing less than the entire flow of patented invention together with the accumulated stock. Each patent was complete enough to be understood by "any person skilled in the art or science to which it appertains," in the words of the original legislation.[62] People had ready access to patent claims at moderate rates or freely in libraries and could acquire the patent specifications and drawings at cost. As the location of *Scientific American* correspondents and contest winners indicated, knowledge was national in scope. Other media complemented publication. In 1826 the *North American Review* recognized the value of the model room at the Patent Office as "a museum of the mechanical arts," and its expansion and reorganization in 1854 opened it to extensive public use. Industrial fairs drew tens of thousands to see working exhibits of inventions. The American Institute's fair in 1852 attracted 100,000 paying customers to examine exhibits on machinery, manufacturing, horticulture, and agriculture, and the New York Exhibition of the next year drew many more.[63]

Publications and Patent Office records were the predominant means to store and spread information. Published patent descriptions could shape future invention. Henry Renwick, then one of six principal examiners, captured the possibilities well in his 1852 report:

> The true practical end of the publication, for those most interested—namely, inventors themselves—is that it will furnish to those now engaged in plans or experiments, a guide to that which has been before done; warning them away from ideas already carried out, and now the property of others; placing before them records showing where experiment has failed, and what remains unattempted; and serving as a sort of dictionary of ingenious mechanical ideas on every art, which may be used in new combinations in diverse arts, and produce new and useful effects.[64]

As Renwick suggested, published information supported several kinds of technological learning that might foster invention, in addition to other benefits.[65] One undesired kind occurred when inventors discovered that their inventive ideas had been anticipated and hence could not be patented. Even this discovery saved

fruitless efforts and could redirect inventive effort to get around the patent. Reflection on patents directed inventors to more promising lines of research. In an analysis of steam engine patents in the annual report of 1843, an examiner noted that "by far the greater part of these supposed improvements, thus patented, have been invented in consequence of a want of accurate information . . . The leading error was the supposed loss of power in the use of the crank to change into a rotary the rectilinear motion of the piston." The result was much wasted effort; studying failures was a means to succeed.[66]

Surveys of technological principles and patent claims shaped inventive objectives. In addition to engines, the 1843 examiners' reports usefully reviewed inventions concerning nails, screws, pins, tools, locks, steamships, textiles, hats, railroads, milling, woodworking, and firearms. Patents often revealed potentially profitable targets; several machines to plane wood, sew cloth, peg shoes, or cut grain were patented before an adequate one was perfected.

Learning took a more universal form when technological principles applied to many sectors, such as the transformation from reciprocating to rotary motion or the turning motion common to churns and washing machines. Principles developed in one context could affect invention in realms unimagined by the original inventor. The presence of cross-industry principles was amply demonstrated in the widespread protest against patents rejected by "illiberal" examiners: "When a man is referred to 'door-plate' as a reason why he cannot have a patent upon a 'fire-place'; and another is told his mode of 'manufacturing an iron fence' is refused on account of a 'glass door-knob' . . . when a railroad-car is rejected upon a 'horse power' and a 'ship combined' . . . we think there are other reasons for dissatisfaction besides the refusal of a patent."[67] Regardless of the merits of the decisions, it is clear that many dissimilar applications involved the same technological principles. We cannot know how often convergent technologies in different sectors led to rejected applications because patent files for rejected applications were destroyed and much rejection involved duplication within the same sector. But the frequency of protests on these grounds, examiners' references to various industries in requesting revision of patent specifications, and the growing trend to insert patent language claiming applicability across sectors all suggest that cross-industry technologies were common and recognized.

Several factors limited the usefulness of published patent information. For even the best-trained person, learning from patent publication was not easy or cheap. Published claims often conveyed little information. Thomas Sloan's 1852 screw patent claimed to employ a "method, substantially as herein specified, of

cutting away the mass of the metal to form the thread, by means of a burr-cutter, in combination with the method, substantially as specified, of finishing and smoothing the threads by means of the chaser."[68] Clearer claims rarely provided sufficient information. Fuller descriptions and engravings in 1853 added much but did not adequately illustrate the invention. Only the full description, drawings, and model would provide complete information, and even this was insufficient to use the technique. The costs of copying descriptions and drawings were not insignificant (even at the 10 cents per 100 words clerks were paid), and to understand all patents would have been very expensive and enormously time-consuming, especially when patents multiplied to thousands per year. A trip to Washington, D.C., was required to examine models.

Moreover, the quality of patents was hard to ascertain. Examiners required only potential usefulness, not actual use, so that readers could not readily assess the importance of a patent. There were guides. *Scientific American* discussed the usefulness of inventions, suggesting, for example, that a balloon claiming to move passengers from New York to San Francisco in three days was flawed or that rotary steam engines were unneeded.[69] Patent examiners' reports about significant advances provided some perspective, but they were guarded and, perhaps due to pressure from slighted inventors, were discontinued in 1853.

On top of this was the problem of information overload. The time required to master patents was substantial. More complex devices required many pages to describe. From 1858 annual patents exceeded 3,000, and the total length of patent descriptions and drawings exceeded 10,000 pages annually. The public needed a guide, but the Patent Office's help was minimal and declined over time. Its early annual reports sorted patents into 22 classes and provided alphabetical lists of patent titles within each class. In 1859 annual reports stopped listing patents by class, providing only a list ordered by the inventor's name and the patent title. Cumulative indexes of U.S. patents published in 1839 and 1846 listed patents by patentee and, within the 22 classes, by patent title. Even without listing claims, the 1846 index exceeded 600 pages. Patent Office staff used the indexes to identify the novelty of current applications, but the indexes said next to nothing about the technological principles used. The next cumulative index did not come until 1873, and it had no patent classification. The need for one was clear; the 1849 *Annual Report* proposed "a general analytical and descriptive index of discoveries and inventions" in which "each could put his hand at once on what might otherwise require years to find, if found at all." But the depiction of the index as "a work that, above all others, would elucidate and serve to perpetuate the essen-

tial and progressive elements of civilization" was not enough to get it funded.[70] As patenting accelerated, both the need for such an index and the difficulty of constructing it grew. Identifying convergent technologies in patents for widely different uses was never attempted.

Private journals and mechanical dictionaries filled part of the gap. The *Scientific American* supplied some syntheses, including a dictionary of chemical patents in 1856 submitted by the examiner Daniel Breed. The journal remarked about how useful it was, but nothing more came of it.[71] *Appleton's Dictionary of Machines, Mechanics, Engine-work, and Engineering,* first published in 1851, included such recently patented inventions as Allen Wilson's sewing machine, George Corliss's gear cutter, and several new screw-cutting machines, coupled with older machinery and descriptions of mechanical principles. Yet such books were often simply compilations from books and journals rather than coherent syntheses of technology.

The patent system and related institutions were far from the mechanical bureau that Evans had envisioned, with its orderly presentation of all inventions and technical knowledge. Instead, inventors suffered from what in 1849 one patent examiner, W.P.N. Fitzgerald, called "the almost boundless and ill-arranged masses of information to be found in the books, the shops, and in the archives of the patent office." The result was patent applications rejected for lack of novelty, something he felt was unavoidable because of the "vastness and variety of the subject," knowledge of which, he wrote pessimistically but accurately, "has never been possessed by inventors, as a class, and never can be possessed, except by comparatively few."[72]

The capabilities of the public formed a further limit. Even if technological information was readily available, most individuals could not comprehend and use the information in patents. Understanding the terminology, the physical relations described, and the drawings was much easier for individuals experienced in the systematic application of scientific principles to useful effect. Such experience was narrowly held. Trained engineers were few. Machinists were more numerous but often only partially grasped technological principles and their representation. In addition, the information in patents was not enough to invent effectively without knowledge of techniques to apply, complement, or manufacture an invention. Experience in inventing also mattered, including understanding experimental procedures, materials, and mechanisms. Using knowledge from patents, not easy for anyone, was more difficult for some than others.

Public Learning from Patenting

There is good reason to expect that learning from patents would stimulate invention, and as the rejection of many applications for lack of novelty showed, there was room to learn. Many inventors consulted patents. The strong interest in acquiring timely information was expressed by the press's impatience when the 1851 *Annual Report of the Commissioner of Patents* was not published until early 1853.[73] Contemporaries expected that knowledge of patents would advance invention, often in different settings. The *Scientific American* wrote that published information "keeps the public mind in fermentation and prevents it from stagnating. 'Knowledge runs to and fro'; the human intellect is quickened and the successful application of one principle but paves the way for its higher application in some other department." It illustrated such spillovers with British iron bridge designs, which were incorporated into large steamships.[74] Reflecting on the Patent Office model room, the patent commissioner noted, "The models are not only of great assistance in the examination of applications, but it is my conviction . . . that from ideas gathered in a visit to these halls have sprung many inventions of great value to the community."[75] The great growth of patenting after 1845 began just after the Patent Office started publishing patent claims and coincided with the inception of *Scientific American.* Published knowledge contributed to this growth. James Gibbs, for example, a Virginia farmer and wool-carding inventor, saw a woodcut of the top of a sewing machine. Interested in its operation, he developed a stitch-forming mechanism. His mechanism was entirely new and formed the basis of the Willcox and Gibbs sewing machine. In this case the article's incomplete information stimulated invention.[76]

Learning from the patenting process and its outcomes could have fostered invention in two ways. On the one hand, the public could have invented based on published information and observation of models. On the other hand, private interactions around patenting could have led to learning and invention by patent applicants or inventive professions. Consider these in turn. If the knowledge flows attending the patent system brought everyone to the technological frontier, all could have invented. Studying patents could spread awareness of problems and solutions. Selling patent rights could overcome the need for industry-specific knowledge to use the invention profitably. Hence, patents and their sale could supply some kinds of knowledge and bypass the need for others, so that one's invention could be independent of one's occupation. Such universal invention was limited by the incompleteness of information transmitted through patents, by search costs, and by the technological capability of people to use that

information. Faced with the incompleteness and uncertain quality of information and costliness of searching, prospective inventors might concentrate their efforts on some patents at the cost of missing technological convergences with others. Individuals without general engineering knowledge might invent in areas in which their knowledge helped target inventive goals or form appropriate solutions. Those with general engineering knowledge would be better able to use knowledge from patents to invent widely. For both groups occupation might affect invention.

I explore the issue by investigating the inventive behavior that would be expected to have resulted from learning from patents. A more direct approach, based on observed learning from patents, has advantages in principle, but it is difficult to exemplify, much less study generally.[77] One extreme possibility—that learning from patenting leveled the playing field, allowing each person to invent all things—can be dispensed with easily. Invention varied by occupation; inventors with technological knowledge gained on the job, including machinists, engineers, draftsmen, and patent agents, patented far out of proportion to their numbers. Other inventors concentrated on types of inventions for which their occupation supplied particular knowledge, suggesting that on-the-job learning directed invention (see tables 4.3, 4.4, and 5.5). Ease of appropriation contributed to this outcome, though assignments also reduced limits to appropriation outside one's industry. To an extent inventors specialized in a single kind of invention; repeat inventors took out two-thirds of their patents in 1 of 34 technology types. Finally, crossover patenting was highest for occupations with general technological skills. The strong role of industry networks in directing patenting suggests that learning from patents or other technological sources outside the workplace might complement occupational learning but did not substitute for it.

Learning from patents could still have directed patenting outside inventors' occupations and complemented learning inside. Inventors often patented broadly; in the all-inventor sample 63 percent of repeat inventors patented in more than one category.[78] A study of 900 inventors in early-industrializing sectors provides useful evidence. Over the whole period inventors averaged 3.7 patents, varying from 2.7 for textile inventors to 4.4 for printing press and firearms inventors (table 7.8). Internal patents (those in the surveyed category) ranged from 1.6 in clocks to 2.4 in firearms, including some not caught by the keyword methods of the surveys. Inventors averaged 1.7 patents outside their surveyed category, led by press inventors, with 2.3.[79] Crossover patenting was common and growing; 45 percent of all inventors and 76 percent of repeat inventors received such patents. Crossover patenting grew from 1.3 patents for those inventing dur-

Table 7.8. Crossover Invention in Early-Industrializing Sectors

	Textiles	Steam Engines	Printing Presses	Clocks	Wood-working	Firearms	Totals
Patentees, 1790–1865	127	84	118	107	127	121	684
Average patents	2.66	3.94	4.45	3.19	3.69	4.40	3.71
Internal patents	1.80	1.89	2.14	1.62	1.91	2.43	1.97
Crossover patents	0.87	2.05	2.31	1.57	1.77	1.97	1.73
Repeat patentees (%)	47.2	59.5	69.5	58.9	60.6	62.0	59.5
Crossover patentees (%)	30.7	53.6	57.6	40.2	50.4	42.1	45.3
Patentees, 1790–1835	87	77	28	30	78	60	360
Average patents	2.11	3.18	3.86	2.90	2.69	2.53	2.74
Internal patents	1.51	1.36	1.71	1.73	1.49	1.23	1.46
Crossover patents	0.61	1.82	2.14	1.17	1.21	1.30	1.28
Repeat patentees (%)	39.1	58.4	78.6	63.3	41.0	38.3	48.6
Crossover patentees (%)	20.7	50.6	53.6	36.7	35.9	31.7	36.1
Patentees, 1836–65	85	65	96	90	100	107	543
Average patents	2.96	3.82	4.75	3.21	4.03	4.64	3.95
Internal patents	2.00	2.05	2.20	1.63	2.05	2.53	2.09
Crossover patents	0.96	1.77	2.55	1.58	1.98	2.11	1.86
Repeat patentees (%)	52.9	60.0	66.7	56.7	65.0	63.6	61.1
Crossover patentees (%)	36.5	53.8	58.3	40.0	54.0	43.0	47.5

Sources: U.S. Patent Office, *Subject Matter Index of Patents for Inventions Issued by the United States Patent Office from 1790 to 1873, Inclusive* (Washington, D.C.: Government Printing Office, 1874); *Annual Report of the Commissioner of Patents,* 1847–65; Edmund Burke, *List of Patents for Inventions and Designs, Issued by the United States, from 1790 to 1847* (Washington, D.C.: J. & G. S. Gideon, 1847).

Note: Patentees are classified into the period in which they had the largest share of internal patents. Over the entire period 684 randomly sampled inventors were studied, including 141 inventors from the 1790–1835 period, with fewer than 20 in three industries. Randomly sampled early patentees were added to increase the number to 360. Hence, the table cannot be used to compare numbers of inventors between periods.

ing the pre-1836 period to 1.9 for later inventors, and the share with crossovers grew from 36 to 48 percent. Inventors did specialize, receiving over half of their patents in the surveyed category, and specialization persisted over time. Many of them also patented in complementary categories, such as engine inventors who patented boilers or locomotives. Yet engine inventors received almost two-fifths of their patents outside any steam engineering category, bringing us back to the question of the breadth of patenting.

Inventors might have patented widely because they learned from patents. Growing crossover patenting after 1835, when knowledge of patents became more available, is consistent with this possibility. But inventors also learned from networks and localities. Network inventors were important in every sector (table 7.9).[80] Their highest shares came in clocks and textiles, which were more geo-

Table 7.9. Patenting and Networks, 1836–1865

	Textiles	Steam Engines	Printing Presses	Clocks	Wood-working	Firearms	Totals
Network inventors							
Share of patentees (%)	63.2	33.3	52.9	72.7	39.5	31.0	48.0
Average patents	5.83	9.57	6.04	3.29	7.40	7.46	5.99
Internal patents	4.33	7.00	4.07	2.46	3.87	6.69	4.23
Crossover patents	1.50	2.57	1.96	0.83	3.53	0.77	1.76
Repeat patentees (%)	75.0	85.7	81.5	62.5	80.0	69.2	74.5
Crossover patentees (%)	41.7	71.4	63.0	29.2	66.7	38.5	50.0
Other inventors							
Average patents	5.14	4.43	7.54	5.78	5.70	8.52	6.69
Internal patents	3.43	1.79	1.63	1.33	2.57	2.41	2.16
Crossover patents	1.71	2.64	5.92	4.44	3.13	6.10	4.53
Repeat patentees (%)	85.7	78.6	100.0	77.8	73.9	96.6	87.7
Crossover patentees (%)	57.1	78.6	95.8	55.6	60.9	79.3	75.5

Sources: See table 7.8.

Note: The study of network inventors is limited to inventors identified in city directories, which provided more information about links to industries, especially among machinists. Network status could be determined for 204 inventors. They were particularly proficient, averaging 6.4 patents.

graphically isolated and had distinctive technologies, and lowest in steam engines, for which network data typically excluded engine users, and in firearms, which concentrated invention during the Civil War. Network inventors averaged nearly twice as many internal patents than did other inventors. Conversely, nonnetwork inventors crossed over more frequently. Three-quarters of them received patents outside the surveyed category, whereas only half of network inventors crossed over. As a result, they received 74 percent of crossover patents. Occupations clearly structured learning and invention, in part because they supplied information pertinent to invention that was not contained in patents.

Learning and invention varied by location. The concentration of textile invention in New England was manifested in its per capita inventor index of 5.9, the ratio of its 69 percent of textile patentees to its 12 percent of population (table 7.10). New England was important in every sector; its overall inventor share was 3.6 times its population share. At the opposite extreme the South's inventor share was only 11 percent of its population share; learning from patents did not overcome other disadvantages.[81] Cities used advantages as centers of learning and industry to average 4.6 times as many inventors per capita as the country as a whole.

Inventors in New England and the Middle States also patented more often than other inventors. For most industries and overall, their internal patent index, which measures the average number of internal patents of their inventors compared to the national average, was modestly higher than one, indicating greater

Table 7.10. Spatial Indices of Patenting, 1836–1865

	Textiles	Steam Engines	Printing Presses	Clocks	Wood-working	Firearms	Totals
New England							
Per capita inventor index	5.90	1.96	2.83	3.59	3.74	3.21	3.57
Internal patent index	1.03	0.72	0.95	1.02	1.18	1.06	1.02
Crossover patent index	0.98	0.94	1.92	1.12	1.00	1.01	1.13
Mid-Atlantic							
Per capita inventor index	0.91	1.88	1.75	1.48	1.19	1.39	1.41
Internal patent index	1.02	1.30	1.11	1.06	0.89	1.01	1.07
Crossover patent index	1.08	1.21	0.63	1.05	1.25	1.16	1.04
South							
Per capita inventor index	0.07	0.04	0.09	0.12	0.11	0.19	0.11
Internal patent index	0.50	0.49	0.91	0.92	0.61	1.01	0.86
Crossover patent index	1.04	0	0	0.63	0.38	0.54	0.44
West							
Per capita inventor index	0.10	0.90	0.56	0.46	0.75	0.67	0.57
Internal patent index	0.50	0.59	0.73	0.73	0.87	0.83	0.77
Crossover patent index	0.52	0.61	0.33	0.51	0.67	0.78	0.63
Cities							
Per capita inventor index	4.35	5.03	6.00	4.11	3.53	4.79	4.62
Internal patent index	1.16	1.23	1.20	1.21	1.33	1.30	1.25
Crossover patent index	0.94	1.06	1.12	0.96	1.66	1.47	1.27

Sources: See table 7.8.

Note: The per capita inventor index is the number of sampled inventors per capita compared to the ratio for the whole country. Internal and crossover patent indices compare average internal and crossover patents in an area, respectively, to the averages in the United States as a whole. Indices over one imply higher average internal or crossover patents than in the nation as a whole. The earliest sampled patent determined patentee location. Population data are for 1850. Urban location refers to cities with over 10,000 residents in 1850.

internal repeat patenting. This contrasts to the South and West, which had internal patent indices that were 86 and 77 percent of the national average, respectively. The difference in crossover patenting was greater yet. Southern inventors averaged only 0.8 crossover patents, 44 percent of the national average. The West was modestly better at 63 percent. Both regions lacked the diversity of learning opportunities enjoyed by eastern inventors. Urban inventors had one-quarter more internal and crossover patents than in the whole country. Learning from patents could not compensate for fewer opportunities to learn near one's home.

The difficulty of understanding patents limited their usefulness for discovering cross-industry applications, yet knowledge of mechanics, chemistry, and drafting made learning from patents easier and perhaps more likely. Such knowledge was concentrated in technological occupations, including engineers, machinists, draftsmen, model makers, and patent agents. These occupations constituted half of inventors in the six sectors after 1836 (table 7.11). They were more prolific, with

Table 7.11. Crossover Invention and Technological Prowess, 1836–1865

	Textiles	Steam Engines	Printing Presses	Clocks	Wood-working	Firearms	Totals
Inventors with occupations	33	34	72	51	61	67	315
Technological occupations (%)	57.6	73.5	66.7	17.6	50.8	41.8	50.2
Average patents	5.58	6.20	7.06	7.44	6.84	8.00	6.64
Inventive breadth	2.37	3.16	3.10	3.56	3.16	3.57	3.07
Internal patents	3.84	3.32	2.88	1.11	2.97	2.64	2.87
Crossover patents	1.74	2.88	4.19	6.33	3.87	5.36	3.77
Other occupations							
Average patents	3.43	2.44	2.96	3.31	3.27	4.90	3.59
Inventive breadth	1.79	1.78	1.79	1.81	2.00	1.79	1.82
Internal patents	2.14	1.22	1.96	2.02	1.93	3.41	2.31
Crossover patents	1.29	1.22	1.00	1.29	1.33	1.49	1.28

Sources: See table 7.8.

Note: Totals are net of three double-counted inventors. Technological occupations include machinists, applied scientists, engineers, patent agents, draftsmen, and model makers. Other occupations with some technological knowledge, including clockmakers and gunsmiths, would, if broken out, form an intermediate group.

nearly twice as many patents as others. They led in internal patents (2.9 to 2.3), but their bigger advantage was in crossover patents, in which they averaged three times as many. They patented in 2.1 categories outside the surveyed category, compared to 0.8 for other occupations. Altogether technological occupations received three-quarters of crossover patents.[82] The same patterns existed before 1836. In all sectors nearly half of 85 inventors had technological occupations, and their 4.6 crossover patents were four times those of others.

What, then, was the significance of learning from publicly available patents? Within industries practitioners monitored inventions. In textile machinery a long-active process of patent licensing kept producers focused on the stream of new techniques. In large part patents were scrutinized for potential usage or actual infringement, rather than to invent based upon them. Patents also signaled future innovations by competitors, which firms might then try to match or supersede. Cyrus McCormick kept careful records of harvesting patents.[83] Sewing machine producers scrutinized new patents; after the sewing machine patent pool formed in 1856, some studied patents to enforce the pool and others to circumvent it. Recognizing that machines were complements, prospective inventors read patents to determine if developments in some machines imposed new requirements on others. Using industry knowledge, practitioners understood patents more easily, and studying patents added to intra-industry learning in directing their invention. For others patents provided knowledge that helped them

enter new industries. As inventors like Gibbs made clear, learning from patents identified problems that directed invention in new areas. Technological spillovers also propelled invention, though the very incredulity of inventors finding patent applications rejected because their principles had been developed for other uses indicates that inventors failed to utilize a great many convergences.

On balance learning from patents was more a complement to on-the-job learning than a substitute. It improved the efficacy of invention but did not dispense with the need for private knowledge. The links of repeat and crossover patenting to occupation and location demonstrated the continued centrality of privately acquired knowledge. Even for those focused on a particular industry, the time involved in studying patents imposed high search costs. Where occupations held widely applicable technological knowledge and interacted with many industries, studying broad ranges of patents was easier. Yet their jobs already provided knowledge of particular techniques, awareness of general technological principles, and contacts with many industries. The patent system was most readily used by those who needed it least.

Private Learning from Patenting

The inventor and patenting occupations gained technological knowledge over the course of their efforts to secure property rights for inventions. Learning from private interactions around patenting provided only a passing advantage if public knowledge was costless, complete, and immediate. Yet because public knowledge was expensive, partial, and hard-to-use, learning from private interactions could provide major advantages for further invention.

Inventors gained little technological knowledge from efforts to secure patents. They typically brought substantially completed inventions to patent agents. They could learn from agents and examiners in ways that improved the invention, but there is little evidence that they involved inventive professionals at early stages of the process. Invention-shaping learning from patents would have played a greater role had inventors hired experts to research solutions to technical problems.[84] The closest cases involved feedback directing inventors toward some lines or away from others, such as the *Scientific American*'s advice to correspondents. Its agency had similar effects. In 1849 Allen Wilson came to the journal's office with models for a rotary steam engine and a sewing machine and sought advice about which to patent. The agency recommended the sewing machine and patented it, beginning a trajectory that led to basic sewing patents.[85] Mechanical or consulting engineers, in cases doubling as patent agents, played some role in early

stages of invention but probably not much. The standard starting point of any patent investigation was a completed idea, with at least a description and drawing; patent examiners refused to judge patentability until the patent application had been submitted. The patenting process largely transmitted information from the inventor to others.[86]

The inventive professions, whose jobs required learning about the whole range of new techniques, were best positioned to learn from patents. Many became significant inventors. Studies of 166 patent agency proprietors and 76 patent examiners and other technical personnel in the Patent Office document their significance. Almost half of all patent agents received patents (table 7.12). Invention was not entailed by their job and might be judged unethical because of possible conflicts of interest, but it was common. Over three-quarters of agent-inventors received more than one patent, compared to three-tenths of all post-1836 inventors. Agent-inventors averaged almost three times as many patents as inventors in general. Perhaps most distinctive was their breadth of invention: agent-inventors averaged 3.1 patent classes, compared to 1.3 for inventors in general. Their broad patent research underpinned the breadth of invention. For agents invention was common, repeated, and widely focused.

Over a third of the Patent Office examiners, commissioners, machinists, and draftsmen employed through 1861 patented, which is especially remarkable in light of the fact that standing examiners could not receive patents. They invented much and widely, averaging 4.2 patents in 2.8 patent classes. Almost half of the 21 patent agents who had worked for the Patent Office received patents. Like other agents, they averaged about 5 patents, which they spread even more widely than other agents did.[87]

Patenting occupations lacked the advantage of producing goods using their inventions, though some became manufacturers. They compensated with knowledge of patent assignment. Two-thirds of agent-inventors assigned patents, overwhelmingly to others, well above the two-fifths of all inventors. The same was true of Patent Office personnel. Agents and Patent Office staff assigned territories frequently. The Washington, D.C., patent agent John S. Brown, for example, held 14 patents, including lard lamps, beehives, stoves, a cart, a baby jumper, a water-draining mechanism, and a toy automaton. Brown could not know how to produce and market such a variety of inventions, nor did he have to. He spread each type by selling rights, typically by state and county.[88] Knowledge of technology and of patenting came together in such assignments.

Lemuel Jenks illustrates the versatility of patent agents. Through 1865 his Boston agency secured patents for shoes, hydraulic machines, cotton hullers, fish bait

Table 7.12. Inventing by Patent Agents and Patent Office Personnel

	Patent Agents	Patent Office Technical Personnel	Agent-Examiners
Number examined	166	76	21
Share with patents (%)	48.2	34.2	47.6
Patentees			
Repeat patenting (%)	76.3	65.4	70.0
Average patents	4.96	4.23	4.90
Inventive breadth	3.06	2.85	3.50
Assignments, researched	52	12	6
Assignments (%)	67.3	75.0	83.3
Assignments to others (%)	61.5	66.7	66.7
Territorial assignments (%)	30.8	33.3	33.3

Sources: Patent agents were identified from city business directories and from Robert C. Post, *Physics, Patents, and Politics: A Biography of Charles Grafton Page* (New York: Science History Publications, 1976). Patent Office personnel were listed in Robert C. Post, "'Liberalizers' versus 'Scientific Men' in the Antebellum Patent Office," *Technology and Culture* 17 (January 1976): 24–54; *Annual Report of the Commissioner of Patents,* and particularly in city directories, including *The Washington Directory, and Governmental Register, for 1843* (Washington, D.C.: Anthony Reintzel, 1843), 118–19; *The Washington Directory, and National Register, for 1846* (Washington, D.C.: Gaither & Addison, 1846), 25; *The Washington Directory, and Congressional, and Executive Register for 1850* (Washington, D.C.: Edward Waite, 1850), 117; *The Washington and Georgetown Directory* (Washington, D.C.: Alfred Hunter, 1853), 40.

cutters, handstamps, nail machines, loom shuttles, water filters, and rock drillers, mostly for regional inventors. His correspondence reveals efforts to identify and claim a wide range of uses for his client's patents. Jenks himself received 10 patents to wash gold, drill rocks, filter water, gin cotton, hold ink, stamp paper, and fire weaponry. He assigned at least 6 patents to seven different people, usually assigning full rights. The range of his patents differed significantly from those of his clients, but after Jenks secured patent rights for a client's handstamp, he invented one of his own. Like many other agents, Jenks purchased patent rights. He owned mining interests and in 1850 purchased half-rights to a steam-powered rock-drilling machine, which he developed and sold. He then received 3 patents for rock drills, assigned patent rights to the same person, but retained an interest in the company and its New York Rock Drill. Jenks, then, was a patent agent, an assignee, an assignor, and a principal in a company using his inventions. He would remain active into the 1890s.[89]

Some agents and former examiners used knowledge to concentrate on chemical and electrical patents, but most patents were mechanical and often quite simple. Invention only modestly mirrored specialization. Leonard Gale, for example, a trained chemist who examined patents in the field, concentrated three of his

four patents on treating "phosphatic guanos" and the manufacture of gas, while the physicist Charles Page examined chemical, heat, and electrical patents and invented an electric locomotive. Yet even they spread their invention more widely, including Page's lock, pipe coupling, and an umbrella that transformed into a headrest. Agents improved patents secured for their clients. Their job was to develop strong patent claims, but they had no obligation to share ideas about any improvements on their clients' inventions. Page's pipe coupler was based upon patents by fire engine manufacturers, for which he was the agent.[90] Patenting professions often invented in leading sectors, including Page's electric locomotive and J. J. Greenough's sewing machine, the first invented in the United States. More commonly, they entered early in the industry's history. Nine invented sewing machines, 5 electrical applications, and 15 the manufacture, distribution, and utilization of gas and petroleum.

Patent agents, former examiners, and other Patent Office personnel came closest to realizing the image of invention-generating public knowledge, in that learning from patents led to their invention. Yet their learning derived from their unique employment as part of the patenting process. Their impact as inventors was limited by their numbers; their patents amounted to about 1 percent of the total issued from 1836 through 1865. Their greater impact came in their influence on others.

Centers and Technological Change

The patent system went far toward meeting two conditions that Oliver Evans had sought to promote invention. It provided incentives to invent by conferring property rights to make patented products, use patented techniques, or sell patents. Almost two-fifths of inventors assigned patents to others, giving significance to a mode of appropriation specific to the patent system. The system's incentives stimulated invention in a way superior to Britain's more costly, less certain system. Evans thought enforcement too lax and the patent period too brief, but the new examination system, vigilant enforcement, and common reissuance lessened these objections.

The system also made technological knowledge public, reducing the costs and uncertainties of inventing. The "mechanical bureau" that Evans had envisioned never formed; had the government systematically classified techniques and patents, conducted experiments about technical problems, and made the results of its efforts known, invention could have been faster yet. But the patent system developed key features of the mechanical bureau. The Patent Office made patents

accessible to the public. Patent examiners established the novelty of patents and enforced a common technological language. For many years publications categorized patents by type, and examiners' reports described important advances.

Factors outside the patent system also spread knowledge about inventions. Governmental bodies including the Ordnance Department, the Corps of Engineers, and the navy diffused methods widely. The Franklin Institute published results of its experiments without concern for patenting. Industrial fairs broadcast new techniques. Civil engineers shared knowledge in person and publications, and machinists spread it among firms. That many techniques arose and spread without patenting does not imply that the patent system was unneeded. Even when first-generation techniques were unpatented, as in textiles, presses, and machine tools, second-generation techniques received patents. Patents offered protection when capital goods could be readily copied or when workers could set up their own firms. That the *Scientific American* published descriptions of unpatented inventions hardly reduced its commitment to, and importance for, patenting. Patents were a central mode of appropriation and communication.

The patent system hardly equalized the inventive playing field. Assignments enabled nonnetwork inventors to benefit from their creations, but network inventors were just as likely to assign and many also owned or formed firms. Patent information was widely available, but it was not equally useful to all. Vast and specialized, the knowledge in patents grew harder to absorb or even search as patents multiplied and already imperfect indexes were eliminated. Hence, many used patents to complement on-the-job learning, including network inventors. Absorbing the knowledge privileged those with generic technological skills and broad on-the-job experience. As technological occupations grew in numbers and sophistication, more people learned widely from patents, including those in the newly formed inventive professions.

Who benefited from the patent system? The system did not overcome private advantages; inventing remained structured by the private distribution of knowledge. Network inventors patented more within industries, technological occupations invented more widely, and cities and industrial regions invented more than other areas. But the patent system benefited many. It provided incentives and learning to networks, technological occupations, and leading areas that helped maintain their advantages. It also enabled some to invent who were not well placed to learn or appropriate. Inventors took targets outside their occupations, including nonnetwork patentees, who made up half the inventors in early-industrializing sectors, or network inventors who crossed over. Patenting benefited

repeat inventors, who used learning and revenue in later inventions. Aspiring capitalists used patents as assets to establish firms. Learning from patenting may have especially benefited those best positioned to learn, machinists and engineers. The clearest beneficiaries were patenting occupations. In such ways the patent system led to more crossover patenting, especially by those with the most cross-industry knowledge.

The three groups most proficient in patenting, and probably in inventing—patenting professions, applied scientists, and machinists—were at the core of technological centers. Each occupation was structured around other purposes: to secure property rights, apply science, or make machines. Pursuing such purposes supplied knowledge that led to extensive invention, which is one reason for the centrality of these occupations. Several aspects of their inventiveness have been documented. In the all-inventor sample technological occupations constituted 30 percent of inventors with known occupations after 1835 and received 40 percent of all patents (table 7.13). They were particularly distinguished by the breadth of patenting, making use of their universal knowledge and wide connections. Whereas other occupations patented in only 0.3 categories beyond the one sampled, technological occupations ranged from 0.6 to 1.4, led by patenting occupations. Machinists were the most numerous, followed by applied scientists and patenting professions. Technological occupations were yet more common among major innovators, in which they constituted 65 percent of the total.

Technological occupations were central to innovation in the six early-industrializing sectors. About half of all inventors in these sectors had technological occupations before and after 1836. They were especially inventive, receiving two-thirds of all patents throughout the period. They had the most internal patents, but their greater advantage was in crossover patenting. Their 2.1 crossover categories far exceeded the 0.8 for other inventors, and they averaged three times as many crossover patents. Their universal knowledge helped identify technological spillovers, some of which led them into early-industrializing sectors.

Although they made up little more than 1 percent of the workforce, technological occupations invented so much because of the high share among them who invented. This was particularly so for principals of firms and for former examiners of the Patent Office. Over two-fifths patented, and they averaged well over twice as many patents as all inventors with known occupations. They also invented more widely. The most technologically capable occupations were also the most inventive.

Invention differed among technological occupations. Patenting professions invented more widely, perhaps a result of learning from patenting.[91] Machinists

Table 7.13. Technological Centers and Invention, 1836–1865

	Machinists	Engineers and Applied Scientists	Patenting Occupations	Other Inventors
All-inventor sample				
Share of inventors (%)	20.7	7.4	2.1	69.8
Average patents	2.93	2.14	3.51	1.77
Share of patents (%)	29.3	7.6	3.5	59.6
Inventive breadth	1.82	1.57	2.43	1.31
Patents in maximum category (%)	67.6	67.9	55.6	80.8
Six early sectors				
Share of inventors (%)	39.0	7.0	4.1	49.8
Average patents	6.62	5.09	9.46	3.59
Share of patents (%)	48.7	6.7	7.4	33.7
Inventive breadth	2.89	2.82	5.15	1.82
Patents in maximum category (%)	60.3	54.5	30.9	72.3
Urban principals				
Share with patents (%)	44.2	40.8	43.4	—
Average patents	4.48	5.26	4.77	—
Inventive breadth	2.17	2.81	2.96	—
Patents in maximum category (%)	64.4	49.1	50.7	—

Sources: See tables 5.2, 5.3, and 7.8; city and business directories.

Note: Urban principals examined include 591 principals of machinery firms, 130 civil and mechanical engineers advertising in business directories, and 221 patent agents and Patent Office technical personnel. In the all-inventor sample 336 inventors had recorded occupations.

concentrated patenting more in a single category; among all samples their share of patents in the maximum category was as high as or higher than other technological occupations. The printing press maker George Gordon, for example, had 18 of his 19 patents in that sector, and Isaac Singer had 19 sewing machines among his 23 patents. Patent agents and engineers were less focused on one industry.

Technological occupations were also central to the invention of others. By designing and making machines or engineering projects or securing patent rights, they increased incentives for others to invent. Through interactions and publications they communicated technological knowledge that reduced the costs of inventing or directed inventors to higher-return projects. Such activities gave shape to a loose-knit inventive community, integrating inventors by common forms of learning and appropriation. The patent system was one structuring mechanism, involving Patent Office staff, patent agents, draftsmen, model makers, courts, patent attorneys, and mechanical experts. Applied scientists, who were organized around universities, infrastructure, science-oriented industries, publications, and civil organizations, spread knowledge of innovations and technological principles. Machinists and model makers made prototypes and produced on

larger scales; they interacted widely with inventors. Patenting was complemented by the open-source diffusion of scientists and the occupational diffusion of machinists.

The inventive community had none of the self-organization of the scientific and engineering professions. Attempts at organizing inventors failed, such as the National Convention of Inventors in 1848, which vowed to fight for patent laws that recognized inventors' interests but never really got off the ground.[92] But the inventive community had regular practices, procedures, and interactions. Inventors had common sources of knowledge, particularly in mechanical dictionaries, Patent Office reports, and the pages of the *Scientific American.* Inventions were regularly, but not always, patented, increasingly through networks of patent agents. Usage was regularized through ties to local firms, new firm formation, and assignment. The community was national in scope, though most heavily concentrated in cities and industrial regions. It was capable of rapid diffusion through regional mobility, national publications, and the ready formation of new firms. Inventors came together in mechanics' institutes, such as New York's American Institute. Its fair managers in 1852 included the press maker Richard Hoe, the stove maker Jordon Mott, and the screw maker Thomas Harvey, who between them had 67 patents through 1865; nine other officers and judges also patented. The fair's 100,000 paid customers witnessed thousands of exhibits that received 1,000 premiums, and firms advertised these premiums as recognitions of quality.[93] The inventive community was voluntary, unplanned, and without explicit organization, yet it was structured by private interactions, government policy, and civil organizations in ways that brought about technological change. The community expanded with the growth of the machinery sector, applied science, and the patenting professions. Technological centers, the inventive community, and the thousands of users of new techniques formed an innovation system that supported ongoing change.

Technological centers all originated around the same time. In the 1830s machinists formed cross-industry links, science expanded in colleges and was applied much more widely, the patent system was fundamentally reformed, and patent agents and examiners came into being. Each technological occupation grew greatly through the Civil War. As they grew, they came to shape technological change over the whole economy, recasting early-industrializing sectors and bringing innovation to new ones. In so doing, they offered a new kind of leadership to economic development.

The Social Basis of Innovation

In 1866 the *Scientific American* proclaimed "the last quarter of a century unparalleled in the world's history" for its advances in science, invention, and wealth. As evidence, it listed the railroad, steamship, telegraph, reaper, and sewing machine, innovations that reshaped American transportation, communication, agriculture, and manufacturing.[1] Their genesis is puzzling. They cannot be explained by the dynamics of existing industries or firms because they formed industries and were developed largely by new firms. No common factor linked them; they responded to different needs and developed in distinct regions through largely unrelated processes. The question is how a wide range of economy-shaping industries arose when no established industries or firms formed them. Given the discontinuity, one might argue, as the young Joseph Schumpeter did, that the ungrounded action of extraordinary entrepreneurs led economic development.

A more institutional interpretation would lead to different conclusions. The *Scientific American* found the "secret" to successful innovation in the activity of "the inventor and the mechanic . . . the pioneers in the great army of progress." Elsewhere the journal added the scientist, noting how science found practical use. Often conceived individualistically, these groups formed a social basis for innovation, structured around a patent system and machinery and engineering sectors. If institutions surrounding machinery, invention, and science provided knowledge and personnel enabling potential innovations to be actualized, then technological centers were essential to the origin and development of major innovations.[2]

The challenge is to explain how innovations were both discontinuous and socially grounded. As Schumpeter argues, major innovations were qualitative breaks, creative transformations of existing conditions, not mere adaptations to changed circumstances. They initiated developmental sequences when emulators followed the innovator's lead, investment grew, secondary innovations occurred,

and the technique spread. If some innovations fostered others, the clustering of innovations might shape the pace of growth.[3]

Yet past developments and current institutions could shape even the most radical innovation. Societies developed knowledge that pertained to various uses but was not applied; institutions affected whether the underutilized knowledge found new uses. Within the firm underutilized knowledge could prompt diversification. Within broader economies limited access to knowledge could stifle innovation. Communication within technological centers could overcome this barrier. Economic, political, and intellectual institutions all could affect whether and when an innovation began and developed. Arguably, the more radical the innovation—that is, the less grounded in the knowledge and practice of the economy—the greater the role of noneconomic factors. Once in existence, the innovation formed its own networks of firms and occupations through which many contributed to its evolution, giving change a collective character. Personal qualities affected who innovated, but institutions formed the means to develop, commercialize, and spread the technique.[4]

The institutions of the machinery sector, the scientific community, and inventive activity offered critical support for the origin and development of many antebellum innovations. They supplied the continuity through which discontinuities originated and spread. Their operation provided solutions to two problems central to Schumpeter's theory: how innovations occurred, and why different innovations occurred in the same period. An examination of the railroad—Schumpeter's classic example of discontinuous change—the telegraph, the reaper, and the sewing machine will make the case.

The Speedy Rise of the Railroad

The railroad was a British innovation led by George Stephenson and his son Robert. After 15 years of effort, they developed successful engines and boilers with features fundamental to all steam locomotives, installed locomotives on the first major railroad, the Liverpool and Manchester, in 1830, and formed the leading locomotive firm. The railroad spread quickly. Success in the United States came in 1831, when Robert L. Stevens imported a Stephenson locomotive for the Camden and Amboy Railroad. Over the next three years steam-powered railroad lines were set up in Delaware, Maryland, Massachusetts, New Jersey, Pennsylvania, and South Carolina. Investment expanded so rapidly that in 1840 the 2,800 miles of U.S. railroad track already exceeded British mileage. By 1860 the United States was home to half the world's railroad mileage.[5]

The question is how the United States could introduce such a radical change so quickly. The United States had the advantage of all followers; it could copy the technique that the leader spent decades developing. But quick success in the international diffusion of technology was exceptional. Although textbooks might suggest that best-practice technology would diffuse immediately, many barriers prolonged or prevented diffusion. Even if equipment and engineering services could be imported, capabilities to service locomotives, cars, and track had to exist domestically. That the United States largely designed and built its own lines, together with the equipment they utilized, made the task more daunting yet.

Many countries had strong demand for transportation improvements but were slow to adopt the railroad. The United States introduced the railroad so quickly because it had the capability and institutions to do so. By 1830 the United States had the capacity to design and produce machinery improvements, to undertake major civil engineering projects, and to transmit these capabilities to new sectors.

The machinery sector contributed organization, capabilities, and personnel. Machinery firms made locomotives; like steam engine users, railroads typically did not make their own locomotives. Machinery firms depended heavily on hand methods, but since the 1820s they also used industrial lathes and boring machines. American machine shops lagged behind their English counterparts but not by much; in the most advanced locomotive shop in the world, Robert Stephenson still overwhelmingly used hand methods in 1837.[6] Locomotive producers trained as machinists. The Steam Engine Report of 1838 listed 24 domestic locomotive manufacturers. Firms that had made steam engines built over 70 percent of 263 domestically produced locomotives, led by Baldwin. The capability to design boilers, engines, and transmission mechanisms; to cast valve parts and cylinders; and to machine engines proved invaluable. Rarely specialized, machinery firms readily added locomotives. Two textile machinery firms made one-sixth of domestic locomotives. Prompted by underutilized resources when textile growth slowed, Locks and Canals diversified into locomotives and machine tools. Other producers had been machinists or iron founders. Related metalworking firms made railroad cars, wheels, and auxiliary equipment. Without prior machinery firms, locomotive companies could not have developed as rapidly, and perhaps not at all.[7]

Mechanized firms employed machinists to operate engines and maintain machinery, and railroads followed the same pattern. From the beginning machinists operated, serviced, and repaired locomotives and cars. When Robert Stevens needed a mechanic to assemble his first imported engine, he hired Isaac Dripps, who had repaired his steamboat engines. Like steamboat engineers, locomotive engineers were skilled in engine operation and repair. Railroad companies built

foundries, blacksmith shops, and machine shops to service equipment, and the master mechanics who ran them had a hand in purchasing and even designing equipment.

Similarly, civil engineers applied skills learned in building canals, roads, and bridges. Railroad companies sought engineers to identify routes that minimized ascents, descents, and curves and to build and maintain railroad lines, tunnels, and bridges. Canal and turnpike companies had employed engineers for related purposes. Design and construction took a year or two, after which many engineers sought employment elsewhere. As the biggest early effort, the Erie Canal was the leading school for civil engineering; its graduates moved to other canals and after 1830 to railroads. Railroad firms emulated earlier engineering methods and organization, employing teams of engineers to survey routes and build lines, bridges, and stations. As lines opened, head engineers were employed as masters of the road, responsible for maintenance and improvement of the lines and coordination with master mechanics.

The Baltimore and Ohio (B&O) was a leader in construction. In 1827 it received the aid of three brigades of federal army engineers. Federal engineers had supported transportation projects since the General Survey Act of 1824, which initially supported canal construction but was soon extended to the railroad. Railroad engineers included Stephen Long, the great explorer, topographical engineer, and locomotive inventor, and the canal engineer William McNeill. McNeill, fellow officer and surveyor George Whistler, and former National Road surveyor Jonathan Knight joined the mechanic Ross Winans on the B&O team examining English railroads in 1828 and 1829. The B&O quickly and effectively developed its lines through difficult terrain because of the contributions of canal and road engineers and the federal government's willingness to train engineers, mainly at the U.S. Military Academy, and to use them to support private railroad improvement.[8]

Many media of technological communication turned to the railroad. In a country widely using the steamboat, the railroad was a natural. The case for railroads was so strong that in 1812 John Stevens, a steamboat pioneer, published a pamphlet arguing that steam-powered railroads were superior to canals and would be a better investment than the Erie Canal.[9] His son Robert at the Camden and Amboy and the Baltimore merchants who formed the B&O took up the challenge. Knowledge of English railroad developments spread readily. From 1826 the *Journal of the Franklin Institute* included many detailed assessments of British locomotives and railroads.[10] Delegations of interested parties examined British railroads, including the B&O team, Robert Stevens, and the first locomotive im-

porter, Horatio Allen. These groups and others were in frequent communication, making the railroad a subject of international discussion.

Using its capabilities and contacts, the United States became a fast emulator. It formed networks that spread learning even before railroad success. American delegations had wide access to British locomotives and railroads. Domestic producers copied the Stephenson locomotive, which was unpatented in the United States. When asked to build a locomotive for a local firm, Matthias Baldwin copied the Stephenson locomotive, after having observed its assembly at the Camden and Amboy. Railroad companies showed their locomotives to engineers and prospective locomotive makers.[11] Innovation occurred so quickly because many supported each other's efforts.

The railroad achieved practicality in the United States through networks that formed in its earliest days and continued to develop alongside it. Interactions around locomotive sale and use, occupational dynamics of machinists and engineers, and publications all contributed. Locomotive firms offered a few models on national and occasionally international markets. Whereas English steam engines were never common in the United States, English firms made three-quarters of the U.S. locomotives built by 1833. In 1838 U.S. companies made three-quarters of the 346 recorded U.S. locomotives, most of them in the Middle States. Domestic firms sold largely within their regions, with some interregional sales. Baldwin was the most diverse; 23 railroads used its locomotives, 9 outside the Mid-Atlantic States. Railroads often ran locomotives from several firms. In 1838 the Boston and Providence used locomotives from Baldwin, Norris, Locks and Canals, Newcastle Manufacturing Company, and three British firms; the Philadelphia and Columbia employed machines from six firms. Master mechanics knew the strengths and weaknesses of their locomotives and communicated this information to locomotive firms and other railroads.[12]

The mobility of civil engineers spread construction knowledge. Early railroads sought experience from surveyors and civil engineers trained in other sectors. Biographical dictionaries suggest the dimensions of the transfer. Of 81 civil engineers who had begun their careers by 1835, railroads employed 49 by 1840, including two-thirds of engineers who were still active. At least half of them had been trained in canals; others had worked on surveying, water supply, and bridge building. Half of the railroad engineers had a college education, half of those in the Military Academy. In 1837, 54 Military Academy graduates worked in railroad surveying and construction, many as civilians.[13] Earlier transportation improvements, college education, and military training provided strong underpinnings for railroad success.

Mobility among railroads and locomotive firms integrated the sector. After having visited England for the Delaware and Hudson, Horatio Allen moved to the South Carolina Railroad early in the 1830s and to the New York and Erie late in the decade. Machinists moved among locomotive firms; Joseph Harrison was trained by Norris, worked for another Philadelphia firm, Eastwick and Garrett, where he became a partner, and then went to Russia. Civil engineers occasionally moved into locomotive construction, such as George Whistler. A Military Academy graduate distinguished at mechanical drawing, Whistler worked as a surveyor before joining the B&O delegation to England. He worked with the B&O and four other railroads and in 1834 organized Locks and Canals's entry into locomotive construction.[14]

Publications helped integrate the railroad sector. The *Journal of the Franklin Institute* included two dozen railroad articles in the decade after 1826, including descriptions of British railroads and assessments of Baldwin and Winans locomotives. From its inception in 1831, the *American Railroad Journal* documented business conditions and new innovations. Many other publications, often by railroad engineers, addressed railroad design. After surveying the B&O Stephen Long wrote several books, including *Rail Road Manual* in 1829, which included studies of track grades and curvatures, and two later books on bridges.

Practical American locomotives developed out of railroad networks. U.S. railroads faced hillier terrain with substantial inclines. With lower population densities and less usage per mile, American roads accepted greater inclines and curves and iron-covered wooden tracks to reduce construction costs. The Stephenson locomotive was too heavy for American tracks and could not navigate the sharp curves without derailing. Invention to solve the problems began even before locomotives were imported. Sailing to England to purchase his engine, Robert Stevens designed the T-rail, a rail shape to support the train and control its motion, which also was cheaper than British alternatives. The T-rail spread slowly in the United States. The second defect was overcome by John Jervis in 1831. Jervis was the chief engineer on the Mohawk and Hudson Railroad when he noticed the instability of Stephenson's locomotive. His solution was a six-wheel engine in which a truck with the front four wheels was unconnected to the rear wheels, hence making it capable of turning independently. The engine powered only the rear two wheels. His locomotive, called a 4-2-0 because it had four leading wheels, two driving wheels, and no trailing wheels, was far more stable than Stephenson's 0-4-0. Being unpatented, the 4-2-0 quickly became the dominant American design of the 1830s.[15]

As Stevens and Jervis exemplify, improvements came overwhelmingly from practitioners in railroads, locomotive firms, and other suppliers. After seeing Jervis's innovation, Baldwin became a leader in 4-2-0 locomotives. He undertook no fundamental changes, but he improved locomotive operation in five patents through 1836, including a crank mechanism moving the wheels and new wheel-making methods. His most important invention was the process of grinding joints for steam pipes to form a better seal than the earlier technique of using red lead and canvas packing, enabling steam pressure to rise from 60 pounds per square inch to 120 pounds.[16]

Others filled out the railroad system. They better articulated the relations of locomotive parts, changed boilers modestly, and developed spark arrestors to minimize fires from live embers emitted by wood-burning locomotives. They improved railroad cars and coupling mechanisms for freight and passenger use and developed braking mechanisms. Wooden ties replaced stone as the base for tracks. Sidetracks and switching mechanisms evolved to allow safer, intensive use of tracks. Improved manufacturing methods for engine parts and wheels increased durability and reliability. The designs of curves and inclines were refined, and improved bridges supported the growing weight and speed of trains.

Such changes, largely incremental in nature, were accomplished by railroad suppliers, master mechanics, and civil engineers. Inventors concentrated in cities making inputs and along railroad lines. Inventors in the three earliest centers, Baltimore, eastern Pennsylvania, and the Camden-Amboy route to New York City, received 70 percent of 190 surveyed railroad and locomotive patents through 1839. Secondary centers along lines in upstate New York, Massachusetts, Virginia, and South Carolina received another 20 percent of patents.[17]

By 1838, only nine years after the first imported locomotive, 59 U.S. railroads averaging six locomotives ran on nearly 2,000 miles of track. No dominant U.S. innovator led the way; many contributed in a process of wide interaction and quick learning. The simultaneous action of many built on machinists' practices in steam engine and textile sectors, without which innovation would have been far slower and less creative. Engineering knowledge, based in colleges and occupational networks, was equally important, supported until about 1837 by army engineers. Inventors applied design skills acquired in earlier invention, including Robert Stevens (steamboat propellers), Baldwin (precision machinery), Winans (cloth-fulling machinery and a plow), Long (steam engines and bridges), and Jervis (leak-stopping methods on the Erie Canal). As the railroad developed, so did a network, eastern in scope, that connected practitioners into a whole, linked

by mobility of engineers and machinists, the dominant 4-2-0 locomotive, locomotive and input firms, and publications.

Railroad Networks and Ongoing Development

The railroad network structured a process that spread the railroad through the Civil War. Potential markets were large, and rapid investment realized much of the potential. From 2,300 miles operated in 1839, railroads expanded a dozen-fold to 28,800 miles in 1859. Total railroad receipts grew from $7.4 million in 1839 to $29.3 million in 1849 and $118.8 million in 1859, and receipts per mile increased modestly. Due to falling rates in the 1840s, passenger-miles and freight ton–miles rose faster still. Railroads extended to the Midwest and the interior South, which together expanded from 5 percent of national receipts in 1839 to 37 percent in 1859.[18]

Expansion followed earlier patterns. Railroads employed civil engineers to construct and maintain lines by redeployment within firms or hiring workers trained on canals and other railroads. Except for transcontinental lines, the government stopped loaning army engineers, but army training benefited railroads when engineers found civilian jobs. Master mechanics ordered machinery and rolling stock, increasingly designed that equipment, and ran railroad machine shops that repaired and occasionally made locomotives and cars. These shops were large; the 18 shops surveyed in the 1860 manufacturing census manuscripts averaged $220,000 in capital and 190 employees.[19] When other lines are included, repair shops probably employed more workers than did locomotive firms.

Railroads bought locomotives from established firms and new entrants. Baldwin and Norris each had built 1,000 locomotives by 1860. A textile machinery firm with three locomotives in 1838, Rogers Locomotive equaled the leaders' output by 1860. Locks and Canals continued into the early 1850s but then largely stopped. After losing B&O contracts, Ross Winans stagnated. These firms built about two-fifths of the locomotives used in 1860. New entrants, largely from steam engine and textile machine industries, supplied the rest. The largest, Holmes Hinkley, used his experience as New England's biggest stationary steam engine producer to build 660 locomotives from the early 1840s to 1860. Boston's Globe Locomotive Works and the Taunton Locomotive Company also emerged from steam engine firms or their workers. Entrants from the textile machinery sector included the Amoskeag Manufacturing Company in Manchester, New Hampshire; William Mason in Taunton, Massachusetts; and Charles Danforth in Paterson, New Jersey. Locomotive firms were large, averaging $230,000 in capital, 260 workers, and a product valued at $260,000—each four to five times the average for machinery

firms. They concentrated in Philadelphia and Paterson, each with over one-third of the national total in 1860, and secondarily in Boston and Taunton.[20] By the 1850s locomotive firms built large foundries, forging shops, and machine shops equipped with lathes, boring machines, and planers, though files and chisels were indispensable. The first movements toward interchangeable-parts production occurred in that decade, with the goals of easing repair and reducing turnover time by making parts simultaneously, not sequentially, relying on their uniformity to allow assembly.[21]

Communication among mechanics and designers in railroad companies, locomotive firms, wheel and car producers, and machine tool firms structured mechanical development. Baldwin's partnerships illustrate the ties. In 1839 he took on two partners, George Hufty, a Baldwin machinist, and George Vail, the son of the Stephen Vail, who supplied wheel tires and axles. In 1842 Baldwin formed a partnership with Asa Whitney, who had superintended the Mohawk and Hudson Railroad. Whitney left to form a railroad wheel factory in 1846. As a partner from 1854, Matthew Baird had been Baldwin's foreman since 1838, when he left his job as superintendent of the Newcastle and Frenchtown's repair shops. These firms were tied to machine tool companies by purchase and proximity: within a twenty-block area of Philadelphia, Baldwin's plant abutted the Pennsylvania and Reading Railroad, Asa Whitney's car wheel shop, and William Sellers's machine tool firm.[22]

Grounded in the experience of practitioners, technological change was built into the railroad network. The most important change was a new driving system. With only two driving wheels, the 4-2-0 had limited traction, and it was too small to pull longer trains, which were increasingly common. After much experimentation on the 4-2-0, the solution came by doubling the driving wheels without eliminating the four-wheel leading truck. The resulting 4-4-0 had better traction and greater power. It was developed in 1836 by Henry Campbell, who, as an associate of Baldwin and the chief engineer at the Philadelphia, Germantown, and Norristown Railway, was firmly ensconced in the railroad network. His design was insufficiently stable on curves and uneven track because the power to the four driving wheels was not well balanced.[23] Andrew Eastwick, an early locomotive builder and assignee of Campbell, advanced an imperfect solution. Eastwick's employee Joseph Harrison overcame the defect with his equalizing bar. These techniques were patented and diffused through assignments and licenses.[24] From 1840 Norris, Rogers, and others built the 4-4-0 in large numbers. As the boiler lengthened over the 1840s and the lead truck and driving wheels became more separated, the 4-4-0 acquired the form of the dominant nineteenth-century U.S. locomotive.[25]

Incremental changes continued throughout the period. Valve gear made better use of the expansive power of steam, culminating in the link-motion cutoff valve, which came be used widely on both sides of the Atlantic from the late 1840s. Boiler jackets reduced heat loss, and the wagon-top boiler prevented the notoriously impure water in American locomotives from fouling the cylinders. In 1858 the French engineer Henri Giffard, through systematic scientific study, patented a water injector to replace the boiler's feed pump. The Giffard injector spread in the United States over the 1860s. Improved spark arrestors, wheel and tire materials, switches, couplings, brakes, sandboxes, headlights, cowcatchers, and bridges improved the safety, durability, and flexibility of the locomotive and track. Trains became longer and heavier and cars more specialized.[26]

Many technological advances were patented. Locomotive, car, brake, and switch patents grew with railroad usage, especially after mileage jumped in 1848. One percent of 508 surveyed patents were issued through 1830, 2 to 6 percent in the five-year periods through 1850, 13 percent from 1851 through 1855, and 67 percent in the next decade.[27] Technological occupations led the way, especially when their members worked in railroad networks. Of inventors with known occupations, machinists received 46 percent of patents, half of them issued to those who made or maintained railroad equipment (table 8.1). Scientific and inventive professions received 11 percent of patents, though some "engineers" drove locomotives. Metalworkers and woodworkers were prominent among other manufacturing inventors. One-third of trade and service workers were employed in the railroad sector in services capacities, many with mechanical skills. Altogether, railroad sector employees received 31 percent of patents.[28] The share of machinists and scientific and inventive professions was highest in locomotive design, in which they received 81 percent of patents. They patented less in other operations, which required less knowledge of mechanisms.

Persistent railroad inventors were central to the sector's development. Locomotive inventors averaged 4.4 patents through 1865 (table 8.2). Two-thirds received more than one patent, and one-half secured multiple patents for railroad-related inventions. Inventors averaged 1.6 locomotive patents; 0.5 for railroad brakes, switches, and cars; and another 0.7 for engines, boilers, and similar railroad-related techniques. Network occupations, including locomotive and wheel producers and railroad mechanics and engineers, concentrated the most on railroad patents, with three-fifths of their patents in railroads and four-fifths in railroad, engines, and boilers. Other occupations had half of their patents in unrelated sectors and only 2.4 patents in railroad-related techniques. Machinists were the most prolific, with 63 percent of all patents and 71 percent of patents related to railroads. Half of the machinists worked in the railroad sector.

Table 8.1. Railroad Patents and Occupations

	All	Locomotive and Generic	Car and Coupling	Brakes	Switching
Patents, number	508	188	88	160	72
Occupation shares (%)					
Machinists	45.7	70.7	14.7	22.2	24.3
Science and invention	10.5	10.5	14.7	9.5	8.1
Other manufacturing	25.5	12.8	38.2	36.5	40.5
Trade and services	15.7	6.0	26.5	25.4	24.3
Agriculture	2.6	0	5.9	6.3	2.7
Network	31.1	46.6	14.7	12.7	21.6

Sources: U.S. Patent Office, *Subject Matter Index of Patents for Inventions Issued by the United States Patent Office from 1790 to 1873, Inclusive* (Washington, D.C.: Government Printing Office, 1874). Occupations were determined from city directories, contemporary industrial surveys, and Population Census Manuscripts for 1850 and 1860, accessed at *Ancestry.com.*

Note: Locomotive patents include 11 generic railroad patents. Occupational shares are for the 53 percent of patents issued to inventors with known occupations.

Table 8.2. Patenting and Assignment by Occupation for Locomotive Inventors

	All	Known Occupation	Network	Non net work	Machinists	Science and Invention	Other Manufacturing	Trade and Service
Inventors	119	75	27	48	44	14	12	5
Patents per inventor								
All	4.4	5.6	6.6	5.0	6.0	3.9	7.1	2.8
Locomotives	1.6	1.8	2.9	1.2	2.2	1.5	1.2	1.0
Other railroad	0.5	0.6	1.1	0.3	0.7	0.4	0.5	0.6
Related to railroad	0.7	1.1	1.3	0.9	1.3	0.9	0.7	0.2
Railroad and related	2.8	3.5	5.3	2.4	4.2	2.8	2.3	1.8
Unrelated	1.7	2.1	1.3	2.6	1.8	1.1	4.8	1.0
Any assignment (%)		60.0	83.3	46.9	67.7	50.0	50.0	33.3
Assignment to others (%)		48.0	66.7	37.5	51.6	37.5	50.0	33.3
Railroad assignment (%)		42.0	77.8	21.9	54.8	37.5	0	33.3
Railroad assigned to others (%)		32.0	66.7	12.5	41.9	25.0	0	33.3

Sources: U.S. Patent Office, *Subject Matter Index of Patents for Inventions Issued by the United States Patent Office from 1790 to 1873, Inclusive* (Washington, D.C.: Government Printing Office, 1874); U.S. Patent Office, *Annual Report of the Commissioner of Patents* (Washington, D.C, 1839–65); Edmund Burke, *List of Patents for Inventions and Designs, issued by the United States, from 1790 to 1847* (Washington, D.C.: J. & G. S. Gideon, 1847). Patent assignment data are from patent assignment records at the National Archives, College Park, Md.

Note: Assignments through 1864 were studied for about two-thirds of inventors with known occupations.

Network inventors more easily commercialized their inventions. Most were master mechanics or superintendents on railroads, and a third of them owned or managed locomotive firms. Both groups could use patents in their own products or equipment. All inventors could sell or license patents. Assignments were common; almost half of locomotive inventors assigned at least one patent to others, and 32 percent assigned railroad patents to others. Many leaders, including Baldwin, Winans, and Robert Stevens, did not assign to others. Although patent assignment enabled inventors outside railroad networks to secure returns for their efforts, network inventors were the biggest beneficiaries. Two-thirds assigned railroad patents to others, five times the share of nonnetwork inventors. The advantages of network patentees in assigning was far greater than in six early-industrializing sectors, in which network inventors assigned about as frequently as others. That network inventors dominated railroad patenting and assignment reinforces Steven Usselman's characterization of railroad innovation as "inside invention."[29]

The railroad was an attractor for other sectors. It drew in firms and workers but also knowledge, inventors, and inputs. Experience inventing outside the sector created capabilities that supported railroad invention. Over one-quarter of railroad inventors began with patents outside that sector, and they received two-fifths of all patents. Many patented steam engines, steam gauges, boilers, and casting methods, which embodied principles that could be applied to railroad invention. Jordon Mott, for example, was a prominent New York stove manufacturer who began his inventive career with a dozen stove patents beginning in 1838. His casting prowess first brought him to railroads, when in 1841 he developed a damp-sand mechanism for increasing traction on railroad tracks. In 1848 he received patents for chilling castings, a common procedure for making railroad wheels, and later received two patents for railroad wheels and one for cars.[30]

The railroad benefited from the largely independent development of machine tools and metalworking techniques. The engine lathe, which Baldwin helped perfect, was quickly applied to locomotives and railroad repair. The planer spread from textile machinery, steam engine, and printing press firms. For firms making machine tools, railroad and railroad input firms were an important market but one dwarfed by demands from engine makers, textile machinery firms, press makers, and others. Two Philadelphia machine tool firms, William Sellers and Bement and Dougherty, formed close relations to railroad and locomotive firms but sold much more widely. Machine tool inventors did not come from the railroad sector and took out only 2 percent of their patents in that sector, far less than in firearms, iron products, and heat-controlling mechanisms. Machine tool firms

played a more direct role when they designed railroad equipment, such as Sellers, the American licensee for the widely adopted Giffard injector.[31]

How, then, did the railroad develop so quickly, widely, and creatively in the United States? Two sorts of processes were at work. Technological centers in machinery, applied science, and invention, just coming to link textiles, engines, presses, and firearms around 1830, provided knowledge, communication channels, and incentives that supported railroad invention and diffusion. The railroad was the first major innovation to benefit from the cross-industry fertilization of these centers. The machinery sector trained agents and organized firms that entered locomotive and railroad production, bringing design and production capabilities with them. Railroad inventors learned from their earlier engine, steamboat, bridge, and machinery inventions. The evolution of the machinery sector supported ongoing railroad development. Applied science organizations, including canal companies, colleges, military engineering, mechanics' institutes, and the technical press, formed the civil engineering capabilities to construct railroad lines, thus grounding innovation in economic and extraeconomic institutions. Journals, mechanics' institutes, and Patent Office publications spread new knowledge.[32] The patent system disseminated knowledge and helped secure returns.[33] Funding sources and large potential sales were required, but without institutions spreading techniques, railroad development would have occurred more slowly and less creatively.

As it built on outside institutions, the railroad sector internalized them into its own network. The network—spanning firms running railroads and making locomotives and other equipment; occupations of railroad mechanics and engineers; markets for equipment, labor, and patents; and railroad journals—was tight and national virtually from the beginning. Locomotive firms competed nationally, and railroads compared information about equipment and conveyed knowledge to other railroads. Interactions between master mechanics and locomotive firms directed design and invention. Mobility between railroads, locomotive firms, and suppliers spread techniques and posed problems for all to address. Invention and diffusion occurred largely within this network. Railroad institutions were linked to technological advances within the broader economy through machine tool markets, labor mobility, patent agents and examiners, publications, colleges, and army engineering. Railroad networks internalized learning and provided regular access to outside changes. Together internal networks and technological centers structured ongoing innovation. Continuity with established sectors helps explain the discontinuity of the railroad, and the railroad evolved along with these broader sectors.

The Diversity of Innovation Paths

Many major innovations reshaped economic life from 1830 to the Civil War. The telegraph rivaled the railroad in the public imagination. The reaper symbolized American ascendance in the Crystal Palace Exhibition in 1851. The sewing machine revolutionized production in the following decade. Each grew rapidly; output in 1865 was from 18 to 40 times higher than when practicality was first achieved (fig. 8.1). Railway track grew from 1,900 miles in 1838 to 35,000 in 1865 and telegraph lines from 2,100 miles in 1847 to 80,000 in 1866. From 450 reapers in 1847, McCormick sold 7,000 at the end of the Civil War, and total harvesting machinery grew three times as fast. Sewing machine sales by leading firms surged from 3,700 in 1854 to 85,000 in 1865.

Why did so many innovations arise in the same period? Schumpeter argued that innovations clustered because one innovation engendered others. The innovation formed knowledge that was used elsewhere, removed obstacles to other innovations, and focused attention on removing limits to its own utilization. On the other hand, technological centers could have supported many innovations. They could have given rise to technologically diverse, largely unrelated innovations that developed along substantially independent paths.

There is little evidence that innovations clustered for Schumpeter's reasons because they had little relation to each other. They differed in core technological principles. The locomotive, reaper, and sewing machine involved mechanical principles, railroad design built on civil engineering, and the telegraph relied on physics. As knowledge differed, so did its means of acquisition (table 8.3). Locomotives, reapers, sewing machines, and telegraphs required machinists' knowledge, combined with awareness of particular applications in steam engineering, agriculture, and thread manipulation. Civil engineering arose from roads and canals. Telegraphs utilized electrical engineering, which had little economic reality in 1830. The principles of the locomotive did little to engender the telegraph, reaper, or sewing machine. Moreover, innovations varied geographically. As documented by 99 major innovators in the four sectors, most railroad and telegraph innovators located in the Mid-Atlantic states, sewing machine innovators in New England, and reaper innovators in the West. Nor did later innovations overcome bottlenecks in earlier ones. The telegraph was used on railroads but found its principal markets elsewhere, and the reaper and sewing machine were hardly generated to improve the railroad and telegraph.

Technological centers underpinned the generation and use of the innovations. Each built on machinery, scientific, and invention capabilities, though in differ-

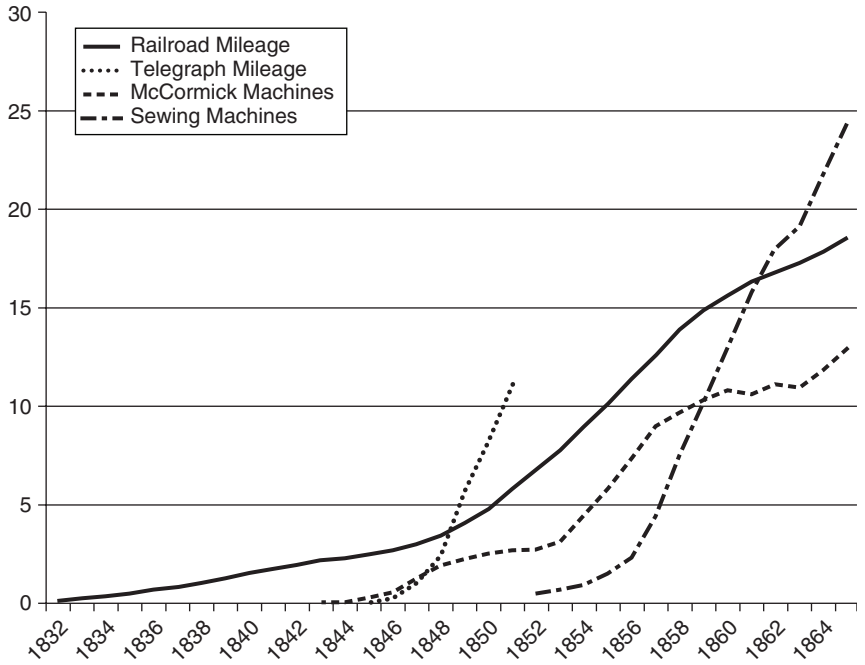

Fig. 8.1. Output indices of innovations (five-year moving averages; year of practicality = 1). *Sources: Historical Statistics of the United States*, ser. Q 321; Robert Luther Thompson, *Wiring a Continent: The History of the Telegraph Industry in the United States, 1832–1866* (Princeton: Princeton Univ. Press, 1947), 240–42; Ross Thomson, *The Path to Mechanized Shoe Production in the United States* (Chapel Hill: Univ. of North Carolina Press, 1989), 103; Grace Rogers Cooper, *The Invention of the Sewing Machine* (Washington, D.C.: Smithsonian Institution, 1968), 40, 89, 112; David A. Hounshell, *From the American System to Mass Production, 1800–1932* (Baltimore: Johns Hopkins Univ. Press, 1984), 161.

ent ways. Innovators acquired knowledge off and on the job. Substantial shares of railroad and telegraph innovators were educated at the Military Academy and other colleges. Over half of telegraph innovators had attended colleges, typically studying science. Not all of them required college training, but it would have been hard to generate the telegraph if none had. Students learned some science in high schools or academies, the highest educational level for 16 to 28 percent of innovators. Most civil engineering and telegraph were mechanicians, as were many locomotive innovators. As the reaper and sewing machine indicate, innovations did not require systematic knowledge learned off the job. From one-fifth to two-

Table 8.3. Major Innovations and Major Innovators

	Railroad: Mechanical	Railroad: Civil	Telegraph	Reaper and Harvester	Sewing Machine
Core technology	Mechanical	Civil	Electrical	Mechanical	Mechanical
Institutions of knowledge acquisition	Machinists, Steam Engineering	Civil Engineers, Canals	Physicists, Electrical Engineers	Machinists, Agriculture	Machinists, Textiles and Clothing
Innovators	34	16	21	18	10
Location of innovations					
Mid-Atlantic	73.5	56.3	76.2	11.1	30.0
New England	11.8	31.3	19.0	5.6	60.0
South	2.9	0	0	11.1	10.0
West	11.8	12.5	4.8	72.2	0
Urban	91.2	100.0	90.5	44.4	100.0
Education of innovators					
College	20.6	62.5	55.0	16.7	0
Mechanician	35.3	75.0	60.0	11.1	10.0
Prior invention	38.2	18.8	42.9	22.2	40.0
Occupation of innovators					
Science and invention	11.8	93.8	52.4	0.0	0
Machinist	61.8	0	28.6	61.1	60.0
Form of appropriation					
Product sale	61.8	25.0	28.6	72.2	90.0
Self-usage	41.2	93.8	61.9	16.7	0
Patent sale and licensing	32.4	25.0	42.9	50.0	60.0

Sources: See tables 4.6 and 8.2.

Note: All figures are percentages except for the number of innovators. These innovators include all with connections to the four innovations, including those with no patents and those with other primary innovations; as such, they differ from the classification of major innovators in chap. 4.

fifths learned from inventing before their major innovation. In each innovation technological occupations trained at least 60 percent of innovators. Machinists predominated in mechanical technologies, and civil engineers improved bridges and other structures for railroads. Half of telegraph inventors had scientific or inventive occupations. Users of new techniques also innovated, including 39 percent of reaper inventors and 20 percent of sewing machine inventors.

Innovators utilized established means to commercialize innovations. The large majority used inventions to change their firms' products or production processes. Most innovators in sewing machines and reapers and many in locomotives owned or managed machinery firms. Civil engineering innovators often used their own telegraph and railroad improvements. Patent sale spread many innovations. Eighty-six percent of innovators patented, and from 27 to 86 percent of them assigned innovation patents to others. Civil engineering improvements

had the lowest assignment rates, though many were licensed. Assignment was typical among the major telegraph systems. As in locomotives, some inventors did not assign important patents or stopped assigning once they built their own plant, including Isaac Singer in sewing machines, Cyrus McCormick in reapers, and Herman Haupt in civil engineering. In addition, 12 percent of innovators, who were concentrated in railroads and the telegraph, spread knowledge through publication.

Typical inventors followed much the same patterns. Scientific occupations dominated telegraph patenting (table 8.4). Telegraphers and equipment designers had internalized recently discovered principles of electrical science, and telegraph inventors frequently interacted with scientists and engineers. Machinists were prominent in every other sector. Inventive professions, mostly patent agents, were significant in sewing and harvesting machinery; a few others lived off patent revenues. Access to particular knowledge explains the unique role of farmers among reaper inventors. Like major innovators, railroad and telegraph inventors located mainly in the Mid-Atlantic region, sewing machines inventors across the East, and each disproportionately in cities. Only for reapers after the mid-1850s was the West important. Reaper inventors were less urban; small towns in Ohio, Illinois, and upstate New York, all near users, played a strong role.

Although different in many ways, innovation paths were similar in important regards. Each relied on broader knowledge-transmitting institutions of the economy. Inventors made good use of the substantial, widely applicable knowledge learned in technological occupations. They also gained technological knowledge off the job. Most used the patent system to protect and diffuse inventions. The universal dimension helps understand innovative success. Each innovation also developed through distinctive networks among practitioners. The 31 percent of railroad patents issued to network occupations underestimates the internal contribution. In other sectors network inventors received the most patents, some by principals of machinery or machine-using firms and others by skilled employees. Each innovation rested both on universal attributes of machinery, science, and inventive centers and on particular networks that structured its origin and spread.

How universal and particular aspects combined to generate innovations remains a question. In the case of railroads universal dimensions fostered multiple innovative efforts, interactions among innovators formed institutions that developed practical techniques, and institutions at least partly specific to the innovation organized the diffusion and development of practical innovations. Other innovations followed broadly similar paths.

Table 8.4. Innovation Patents by Occupation and Location

	Railroad (%)	Telegraph (%)	Reapers and Harvesters (%)	Sewing Machine (%)
Patents	508	178	206	227
Occupational shares				
Machinist	45.7	4.9	44.6	64.5
Applied science	7.9	64.6	0	2.4
Invention	2.6	6.9	22.3	13.6
Other manufacturing	25.5	16.7	7.6	16.6
Trade and service	15.7	6.3	2.5	1.2
Agriculture	2.6	0.7	22.9	1.8
Network	31.1	67.4	56.7	54.4
Locational shares				
Mid-Atlantic States	56.1	64.0	54.1	46.3
New England	20.1	23.6	2.9	43.6
South	5.1	3.9	4.4	2.6
West	18.7	8.4	38.5	7.5
Urban	53.5	74.2	27.3	64.8

Sources: See tables 8.1 and 8.2.

Note: All figures are percentages except for the number of patents.

Originating Innovations

The need for innovations was widely recognized, and many attempted to meet it. Whereas U.S. railroads built on foreign techniques and networks, other innovations had to form both. The value of communicating faster than people could travel had led to optical and auditory signals over many centuries, culminating in the French optical telegraph. Thirty-three reapers had been invented in Britain by 1831, 22 in the United States, and 2 each in France and Germany. Seventeen stitch-forming machines preceded Elias Howe's invention.[34] Yet successful innovators knew little of earlier inventions. Aware of optical telegraphs, Samuel F. B. Morse claimed to know nothing of other electric telegraphs, which, given the timing and distinctiveness of his invention, seems possible. Cyrus McCormick knew only his father's reaper, and Howe was unaware of other sewing machines. The absence of networks relegated inventors to making the same mistakes as their predecessors.

Innovators benefited from surrounding institutions. For the sewing machine and reaper occupations spread knowledge of machine design and cloth-joining and grain-cutting methods, and the patent system provided incentives and knowledge. The telegraph rested more on noneconomic institutions. Expanding electrical knowledge, occurring virtually entirely within pure science, had only recently formed what Joel Mokyr called the "epistemic base" of the tele-

graph, including electrical and electromagnetic discoveries by Alessandro Volta, Hans Oersted, Michael Faraday, and Joseph Henry. The international community of scientists spread the knowledge in European and American journals, including the *American Journal of Science and Arts* and the *Journal of the Franklin Institute.*[35]

The development of technological centers fundamentally distinguished innovation in the 1830s and 1840s from that of a half-century earlier. Their role was particularly clear when the private economy was least capable of solving technical problems. An underappreciated artist, Morse was well versed in science. At Yale he had studied sciences, including electricity, with professors such as Benjamin Silliman Sr. Morse was already an inventor; he and his brother patented a pump in 1817. In New York, where he became a professor at what would become New York University (NYU), Morse attended electrical lectures and talked with science professors. Utilizing this background and discussions of electricity on his fabled 1832 trip across the Atlantic, Morse developed early versions of each of the key elements of the electric telegraph, the use of electric circuitry to send messages, adequate sending and receiving systems, and a code to represent the content of communication.[36]

McCormick lacked the advantages of inventing in a center of technological knowledge. He grew up on a well-off Virginia farm in an Appalachian county that did not possess a machine shop in 1840 or 1860. His farm did have a blacksmith shop, and his father invented machines to thresh and break hemp, a horsepower, a bellows, and an improved grist mill, received four patents, and for 15 years had developed reapers. Cyrus produced and sold a few of his father's machines. He also inherited his father's interest in invention. He journeyed to Washington, D.C., to patent a hillside plow in 1831, patented another plow in 1833, and made and sold modest numbers of plows. Knowing firsthand the requirements of grain harvesting and the defects of his father's reaper, Cyrus invented and used a machine with the design features of an adequate reaper in 1831, though in primitive form. He patented the machine in 1834, prompted by a notice of Obed Hussey's 1833 reaper patent.[37]

The sewing machine developed in the most favorable setting in the United States. Howe was a machinist in Lowell and Boston, where he acquired knowledge of mechanical design, machine production, and thread manipulation. Workplace conversations informed him of inventive opportunities, including the sewing machine. Friends supplied financing. His lockstitch machine, patented in 1846 after two years of development, solved the core problem of mechanical stitching.[38]

Initial telegraphs, reapers, and sewing machines were promising but impractical. They succeeded only after others had improved their design and production. Practicality occurred faster when existing networks communicated knowledge. Surrounded by such media, Howe was quickest to achieve success. Morse and McCormick first had to forge connections to new groups.

Had others not entered the picture, Morse's solutions would have remained brilliant anticipations, failures to be resuscitated later by antiquarians and patent lawyers. His knowledge of electricity and machinery was too shallow to develop his ideas to practicality. After four years spent trying, he formed several critical contacts. The most important was Leonard Gale, a scientist, NYU geology professor, and friend of Joseph Henry. Gale introduced Morse to Henry's work on electromagnetism. An 1831 article in the *American Journal of Science and Arts* described the principles of an experimental electric telegraph and suggested two basic changes that Morse introduced: multicell batteries to increase voltage and a reconfigured electromagnet. Gale helped design and perfect electrical mechanisms and in return received one-sixteenth of the patent. Morse also used the expertise of others, including Charles G. Page, second only to Henry among U.S. physicists, who helped solve problems in electrical transmission and the receiving magnet.[39]

Alfred Vail linked Morse to the world of machinery. The son of Stephen Vail, who made car wheels for Baldwin, Alfred headed his father's machine shop. Morse recognized that his machinery was primitive, and when Vail, an NYU graduate, became interested in telegraphs, Morse formed a partnership in which Vail got one-eighth of Morse's patent in exchange for constructing equipment and financing patent applications. Vail designed much of the equipment and came to develop electrical technology, including Page's magneto. With Gale's scientific insights and Vail's design skills, Morse formed a telegraphic system that communicated over a few hundred feet of wire, then 1,700 feet, then 10 miles. He received a caveat from the Patent Office in 1837, a patent in 1840, and continued developing his system.[40]

Practicality could not be demonstrated without commercially viable use, which required a project of such scale and uncertainty that private financing was hard to secure. Public policy proved essential. In 1843 a federal appropriation of $30,000 funded a Baltimore-Washington telegraph located along a spur line of the B&O. Ezra Cornell supplied construction skills. A mechanic and salesman of patented plows, Cornell built a plow for laying underground cables and, when these failed, joined Morse, Vail, and Page in designing a system strung along poles. Success came when the words "What hath God wrought?" were transmitted in 1844.

Morse took a dozen years to develop a practical telegraph, but McCormick took even longer, partly because of his isolation from the machinery sector. He understood that mechanically skilled workers would have to assemble, test, and adjust the machine, train users, and undertake repairs; for this reason he confined early sales to nearby counties. Making even a few successful machines a year proved difficult; a dozen years after the machine had been invented, McCormick still had to have the knives made 20 miles away. He improved the reaper continually, such as by adding a seat for the worker who raked cut grain. To widen sales, McCormick licensed patent rights in Virginia and in grain centers of western New York, Ohio, and points west. Licensees' products were often poor, and McCormick's reputation suffered. Only in 1846 did he or his contractors produced as many as 100 machines of adequate quality, and he did not produce 700 machines until 1848, the year his patent expired. By then he had decided to build his own factory in Chicago.[41]

Whereas McCormick was involved throughout the evolution of his machine, Howe was the exact opposite; his machine achieved practicality quickly, and he had little to do with it. When in 1847 his Boston sewing demonstrations elicited no interest, he moved to England, where he sold his British patent rights and adapted the machine to sew corsets. Returning to the United States two years later, Howe found many infringing sewing machines; his future role would come in the courtroom. In classic network fashion Boston-area machinists, tailors, and inventors developed his machine. John Bradshaw, another Lowell-trained machinist, improved the loop-forming mechanism. Based on his invention, Charles Morey and Joseph Johnson designed a chain-stitch machine and sold at least 50 of them. In a basic improvement of the Morey and Johnson, John Bachelder introduced continuous feeding and a horizontal, reciprocating needle. The tailor Sherburne Blodgett developed a defective machine in 1850, which proved important because Isaac Singer noticed and overcame its defects and subsequently formed one of three leading companies. The other two were shaped by early nodal machines, Grover and Baker by observing Blodgett's machine and Wheeler and Wilson by inventing around an infringement suit by the owners of the Bradshaw patent. Linked by nodal machines, a community of machinists and mechanics brought the sewing machine to practicality by 1854, when Allen Wilson developed a fully adequate feeding mechanism. The machine became feasible commercially when cross-licensing and an 1856 patent pool sorted out property rights.[42]

The railroad, telegraph, reaper, and sewing machine all became practical by internalizing scientific, mechanical, and inventive capabilities from the broader economy and forming innovation-specific networks that spread and developed

knowledge. The telegraph network included telegraph firms, electric instrument suppliers, engineering labor markets, and parts of the scientific community. Machinery firms produced and developed equipment for each innovation; where mechanical skills were weaker, including rural Virginia and among McCormick's contractors, practicality came later. Each sector depended on patenting to gain financing and appropriate returns, and in each sector later patents developed earlier ones.[43] Some network relations were cooperative, such as Morse's relation with consultants and assignees or McCormick's work with contractors who made faulty reapers. Others were competitive, including efforts to form telegraph systems that did not infringe on the Morse patent and McCormick's jousting with Hussey.[44] But all of them communicated knowledge that developed the innovation to practical form.

Realizing Potential by Deepening Networks

Realizing an innovation's potential depended on practicality and the path through which it was achieved. Practical innovations led to rapid growth that greatly broadened the groups connected by the new technique, spreading learning and invention. The networks that formed as the technique became practical structured its later development.

Firms that achieved practicality led the penetration of the market. When the government failed to buy his patent, Morse and his new partner, former postmaster general Amos Kendall, formed the Magnetic Telegraph Company. Its chief asset was a Morse assignment giving it the "exclusive right to constructing a line of telegraph under said patents from the City of New York, to the cities of Philadelphia, Baltimore, and Washington." Seeking an orderly expansion, Morse and Kendall licensed rights to new telegraph companies for designated areas, taking stock as partial payment, including Samuel Colt's line "from New York City to Sandy Hook, Long Island, other parts of Long Island and the New Jersey Shore."[45] Competing techniques and dissension among Morse's partners undercut this plan, but the stampede of lines effectively spread the use of the telegraph.[46]

McCormick continued to lead reaper production, though many others entered the market when his patent expired. He tried to extend his patent and sue others under later patents but failed on both counts. Cornelius Aultman, Ephraim Ball, and J. H. Manny became formidable rivals. The three dominant sewing machine firms in 1854 held their position through the Civil War, bolstered by their leading status in the patent pool. They produced 80 percent of known machines in 1854,

60 percent of the machines in the 1860 census, and 66 percent of the machines the patent pool licensed in 1867.

Each innovation formed a system of interacting agents. Like the railroad, the telegraph became a large-scale national system needing standards about methods, equipment, language, and message priorities, though agreement was slow in coming.[47] Telegraph engineers frequently moved among lines. As a radical innovation, the telegraph formed wholly new professions, electrical engineers to establish and maintain service and design equipment, and telegraphers, who required technical knowledge to operate and maintain equipment. Networks extended to urban electrical instrument makers, battery producers in the chemical sector, makers of telegraph wire and insulation, and a few independent urban electrical engineers and electricians.

Machinery firms dominated reaper and sewing machine development. Users were smaller and less technically skilled than were telegraphs or railroads and did not impose standards or designs. Firms' agency systems demonstrated, sold, and repaired machines, and in the process learned from users. Machinery firms centralized production in part to improve quality. McCormick concentrated production in his own plant in 1850, though he continued to contract for specialized parts. Leading sewing machine firms built their own plants in the mid-1850s. Both industries drew from well-established markets for machinists, blacksmiths, and carpenters.[48]

Each network involved machinery firms. Over 4,000 workers made locomotives and at least as many worked in railroad repair shops (table 8.5). These establishments were the largest in the machinery sector. By contrast, telegraph instrument firms, the progenitors of the electrical machinery industry, averaged but 7 workers. Harvesting and sewing machine firms were more typical. Although large firms continued to lead, others competed effectively, including the 37 that reduced McCormick's share to one-quarter of the market for reapers and mowers in 1860.[49]

Most firms in innovative sectors patented. Among 1860 machinery firms lasting at least four years, at least one principal (typically a partner) patented in almost 70 percent of locomotive firms, 80 percent of sewing machine firms, and all harvester and telegraph instrument firms. Inventive principals averaged 10 patents in locomotives, 5 to 6 in sewing and reaping machines, and 2 in telegraph instruments. Many firms also purchased or licensed patents.[50]

As output and learning grew, invention accelerated. Already practical in the late 1830s, railroads averaged six times as many patents after 1855 (table 8.6). After gaining practicality around 1847, telegraphs doubled their annual patenting a

Table 8.5. Innovation and Machinery Firms, 1860

	Locomotive	Railroad Repair	Telegraph Instruments	Reaper and Harvester	Sewing Machine
Firms, number	19	18	8	38	57
Capital, average	$233,300	$216,500	$5,900	$44,800	24,500
Value of product	$262,800	$154,400	$15,800	$71,100	$98,300
Employment, total	4,934	3,440	55	1,682	2,075
Employment, average	259.7	191.1	6.9	44.3	36.4
Employment, median	175	95	6	25	10
Employment, maximum	720	990	16	200	570
Largest employer	Rogers Locomotive	Baltimore and Ohio	Thomas Hall	McCormick; Aultman	Wheeler and Wilson
Surveyed for patents	13	0	7	13	37
Share, principals with patents	69.2%	—	100.0%	100.0%	78.4%
Patents per inventor	10.4	—	2.0	6.5	5.0

Source: U.S. Census Office, Manufacturing Manuscripts from the Eighth Census, 1860 (available in national archives and in state archives in Conn., Del., Md., N.H., N.J., N.Y.).

Note: The study includes counties with about 60 percent of all machinery employees in the United States and virtually all of the output of locomotive and sewing machine industries.

decade later. Sewing machine invention tripled after practicality, and harvesting patents, stimulated by accelerating diffusion and the expiration of key patents, grew from under 2 annually in the late 1840s to over 50 after 1855.

Network inventors undertook much of the accelerated patenting. They made up from three-eighths to one-half of those with known occupations, and others with generic occupational listings would add to their ranks (table 8.7).[51] Overall their share of patents was a little higher than their share of inventors. More important, their share of patents related to the innovation was far higher, ranging from 54 to 67 percent. Most inventors assigned at least one patent to others. In each innovation one-third to two-thirds of network inventors assigned innovation patents to others. Nonnetwork inventors varied; in locomotives and telegraphs a much smaller share assigned innovation patents to others, but in sewing machines and reapers the share was larger than for network inventors. Perhaps in large-scale technological systems such as railroads and telegraphs, access to specialized knowledge gave advantages to network inventors, but high capital costs led them to appropriate returns more through assignment. Reapers and sewing machines were simpler devices, and network inventors, better able to set up machinery firms, had less reason to assign. For each innovation a larger share of network inventors gained potential usage in their own firms or through assignment.

Table 8.6. Major Innovations: The Time Path of Patenting

	Railroad	Telegraph	Reapers	Sewing Machines
1821–25	2	—	1	—
1826–30	5	—	1	—
1831–35	19	—	3	—
1836–40	33	1	0	—
1841–45	13	4	3	4
1846–50	29	30	9	13
1851–55	67	24	20	104
1856–60	189	62	274	381
1861–65	151	57	253	339

Sources: See table 8.1.

Ongoing invention furthered diffusion. Invention improved core technologies, including relays to enable long-distance telegraphy and cables to cross rivers, channels, and, for a few months before breaking, the Atlantic Ocean. Suppliers' invention improved the telegraph, such as superior insulation and wire manufacturing developed by rubber and wire firms. Reapers increased in durability and adaptability to varying climactic conditions; McCormick's model changed each year to this end. Self-raking reapers lowered labor costs. Attachments and specialty machines extended mechanized sewing. Sewing machines penetrated shoemaking in light uppers, then heavy uppers, and then shoe bottoming.[52] The sewing machine thus revolutionized two of the three largest industries, clothing and shoes, by means of knowledge and agents from the third, cotton textiles.

Table 8.7. Innovations by Inventor Type and Patent Assignments (percentages)

	Locomotive	Telegraph	Reapers and Harvesters	Sewing Machine
Network inventors				
Inventors share	36.0	49.2	45.2	37.0
Patent share	42.8	52.3	42.9	41.6
Innovation patent share	55.4	67.4	54.4	55.6
Any patent assignment to others				
Network inventors	66.7	63.6	68.8	57.1
Others	37.5	52.6	90.9	74.1
Assignment in innovation to others				
Network inventors	66.7	54.5	50.0	35.7
Others	12.5	21.1	72.7	48.1
Potential usage				
Network inventors	100.0	68.2	87.5	85.7
Others	31.3	21.1	81.8	59.3

Sources: See tables 8.1 and 8.2.

Production changes improved quality and reduced costs. Each innovation utilized engine lathes and planers. Locomotive and especially sewing machine firms were leaders in precision metalworking; McCormick remained more dependent on forge-and-file technology. As scale grew, so did mass production. In 1860 one firm made 250,000 locomotive and car springs. From the late 1850s sewing machine firms moved toward interchangeable parts. Wheeler and Wilson built a factory using mass production machine tools developed in the firearms sector, as organized by three one-time firearms contractors. The Willcox and Gibbs firm took another route when it employed Brown and Sharpe to make its machines. By 1867 Brown and Sharpe sold milling machines to four firms making railroad equipment, seven making sewing machines, and one making reapers.[53]

After these machines had become practical as well as before, networks spread knowledge that led to ongoing invention and product improvement. The development of the core technology was largely a result of these internal dynamics. In addition, outside developments in machine tools, casting methods, wire forming, woodworking machinery, machine design, and electricity supported internal change. Innovations succeeded because of the combination of internal dynamics and external support.

Innovation Processes and Simultaneity

Innovations embodying new technological knowledge were social products in two senses. First, innovators used knowledge generated for other purposes by learning from technological centers surrounding machinery, science, and invention. Because not everyone had access to such knowledge, those who did had advantages in innovating. Yet many had access so that many could innovate at the same time. Second, interactions within the innovation process were sources of learning that advanced innovation. By developing their own problem-solving networks, innovations shaped their own development, though always in relation to social need and outside changes. The puzzle of explaining the genesis of discontinuous innovations is in part solved by noting that innovations developed out of existing institutions and on this basis built new ones—new firms, new kinds of markets, even new occupations.

The twofold character of social processes of innovation has bearing on the simultaneity of major innovations in the antebellum period. Innovations followed different paths with separate networks, distinct kinds of knowledge, and varying institutions. Railroads, telegraphs, reapers, and sewing machines were developed by different people, in distinct regions, who had little contact with

one another. Although telegraphs occasionally followed railroad tracks or were licensed to railroad firms, most telegraph sales came from elsewhere. Hence, the simultaneity of innovations cannot be explained by clustering when a central innovation gave rise to others. Adding petroleum production, Corliss engines, cylinder printing presses, and woodworking machines would reinforce this conclusion.

The first characteristic of the innovation process is more helpful. The rise of so many innovations in the late antebellum period was in part due to the presence of an effective machinery sector, an applied science community, and strong inventive institutions.[54] Technological centers underpinned innovations across the economy and so helped account for their simultaneity. Centers' knowledge shaped innovations, including general knowledge of machine design, the strength of materials, metal fabrication, and electricity and particular knowledge of boiler pressures, bridge support, electromagnets, and thread manipulation. One reason the United States developed many, varying innovations was that innovators had access to many kinds of knowledge. Without distinct knowledge bases, the United States might well have succeeded in some innovations and failed in others. Without science the United States could have developed the sewing machine but not the telegraph; without machine tool developments the reaper might have developed, but the locomotive or sewing machine would have been hobbled.

Machinery, inventive, and scientific institutions spread knowledge in various ways. Electrical knowledge diffused through education and scientific networks. Civil engineering spread through these media, the actions of government engineers, and the engineering occupation. Publication became increasingly more important. Many innovators contributed by publishing technological treatises, including one-quarter of major telegraph and railroad civil engineering inventors. Sales of capital goods, machinists' mobility, and diversification by machinery firms spread mechanical knowledge. The patent system transmitted knowledge through publication, observation of models, and the actions of patent agents. Knowledge-spreading institutions concentrated in urban areas of the East and the Midwest, but they also integrated the United States with European developments. Public knowledge was not free or universally available, but the access cost declined with involvement in appropriate networks. Innovation in capitalism rested essentially on knowledge that was not the property of any individual.

Centers also provided procedures, agents, and incentives for innovation. Aspects of the organization of machinery firms and canals were emulated in innovative sectors. Established markets supplied machinists and engineers. Innovators were often trained in other sectors and gained an interest in the innovation

through communication with others. Individuals connected with centers had technological and organizational knowledge to innovate, and they disproportionately led the innovative process. The patent system helped secure returns, but innovators also had to acquire production and design skills, financing, and the inventions of others.

Innovations formed their own networks by internalizing economy-wide institutions, but they did so in different ways. The railroad and telegraph depended most on science. The sewing machine, locomotive, and reaper relied, respectively, on textile machinists, engine makers, and blacksmiths. Although capital goods firms developed everywhere, they led innovation in sewing machines and reapers but were secondary in telegraphs. Patenting was universal, but territorial patent assignments were vital for telegraphs, patent pooling for sewing machines, and patents embodied in the firm's products for many locomotive and reaper firms. Each innovation trained workers who left for employment in other firms or to set up their own firms. Mobility of workers and new firm formation were sources of positive externalities. The self-interest of innovators, the public character of knowledge, and positive externalities were each essential to the innovation process.

Once in existence, innovations helped reshape the economy. They were attractors that reoriented the activities of other firms and workers. They changed demand patterns and the location of production. Innovations contributed new technical knowledge, new problems to ponder, new occupations, and new organizational forms such as nascent managerial firms in railroads, telegraphs, sewing machines, and reapers. They added to the depth and range of machinery, inventive, and scientific institutions, which supported other innovations. Technological centers, innovations, and feedbacks between them propelled the economy before the Civl War and would continue to do so afterward.

CHAPTER NINE

Technological Leadership

To discover the truth behind the stories of American steamboats, the French minister of maritime affairs sent a naval engineer and graduate of the French Polytechnic, Jean Baptiste Marestier, to assess American accomplishments. Studying dozens of boats in 1819 and 1820, Marestier issued a precise, circumspect, but obviously positive report. Reflecting on the report, the Royal Academy of Sciences concluded that Americans were "already reaping immense benefits." In additional to the direct benefits, they projected some indirect results: "When a new kind of useful mechanical power is introduced into some branch of human endeavor, a large number of other branches soon profit. It accelerates the general progress of invention. It gives to the nation which first seizes upon it, or which exploits it to the greatest extent, an important degree of superiority over other nations."[1]

The academy was addressing a fundamental question: did one sector lead the technological development of the whole economy? Leading sectors have long been part of the explanation of capitalist development. Cases have been made for steam engines, textiles, firearms, and the railroad, and each did advance technology elsewhere in the economy. For Joseph Schumpeter textiles and engines led an Industrial Revolution long wave, and the railroad led the next. He presents one idea of leadership: one or a few innovations had great effects on many sectors, while these sectors had little effect on the leaders. Technological knowledge cumulated as leaders affected followers and as new leaders arose. In an alternative vision many sectors affected others, each also benefiting from innovations made elsewhere. Technology accumulated as knowledge developed in many sectors, spread among them, and gave rise to new sectors.

Understanding the role of leadership involves knowing what it means to lead. Schumpeter examined the total impact of innovation on economic growth, but here I will address the narrower question of whether technological knowledge spread among important uses in many industries.[2] Technologies led when they

spilled across industries. Spillovers could have been reciprocal or unidirectional. If innovative sectors generated some spillovers and benefited from others, then each was both leader and led. Mutual externalities interlinked sectors, without a distinctive leader. If, however, a sector had effects on other sectors that they did not have on it, then it alone led. For such "strong leaders" positive externalities flowed in one direction. Without the leading sector followers might not have developed or at least would have had to solve problems that the leader solved for them. A second issue concerns the number of leaders. Along Schumpeterian lines one sector could have led the whole economy; it would have been indispensable for economic development. Alternatively, many leaders might have supported later developments. Finally, mechanisms to spread knowledge must have existed. Networks organized innovations within industries and their capital goods suppliers, but how did knowledge move to other industries?

The presence of technological centers bears on each issue. Centers transmitted knowledge across industries, providing means for leaders' knowledge to spread to followers. Because universal knowledge arose in many sectors, centers spread knowledge from leaders and to them. Particular knowledge developing in earlier industries more readily spun off to other industries when centers had been formed. Before they existed, industries developed more autonomously; early industries might have been strong leaders because they led later industries with relatively little input from changes in the followers. The formation of centers from the dynamics of many industries suggests that no industry led development by itself. The multiplicity of leaders limited the role of any one of them. The rise of centers reduced the autonomy of any industry yet increased their combined spillovers, speeding the cumulation of technological knowledge. If so, the breadth of technological change on the eve of the Civil War economy emerged from the leadership of many industries and the structures interlinking them.

Textiles, Firearms, and Early Industrializers

Industries could lead because their technological principles applied elsewhere or because their products were used in many industries. Textiles and firearms exemplified the former and engines the latter. Considerable evidence suggests that textiles and firearms were strong leaders. For each, changes originating in the industry were principal determinants of changes in other sectors, and changes in other sectors were much less significant in its evolution. Of course, any innovation relied on existing capabilities, such as the woodworking and metalworking skills Slater secured from Sylvanus Brown and the Wilkinsons.[3] The key

is whether the industry's development depended basically on *changes* in other sectors.

The textile industry well illustrates the disproportion of spillovers. It did benefit from developments elsewhere. Paul Moody used his background in machinery and nail-making innovations to develop Francis Lowell's machinery. Textiles used machine tools developed for other purposes, such as the planer, which Locks and Canals helped introduce in the United States. The French water turbine improved power delivery. Otis Holmes's Springfield Armory experience aided in building the milling machines that his Hadley Falls plant used to make textile machinery.[4] Yet as chapter 2 demonstrated, many more textile innovators and producers were trained within the industry. Especially before 1835, textiles developed substantially through its own networks.

Knowledge gained in textile production had major effects elsewhere. Machinists, commodities, firms, and ideas spread knowledge widely. Machinists and inventors used production skills and technological knowledge to transform production in other sectors. Machinists moved outside textiles, beginning with the originators of the textile factory. David Wilkinson trained Jeremiah Arnold, who continued Wilkinson's interest in making threaded screws when he set up a press for making nuts. The Providence Tool Company, one of the premier U.S. hardware firms, developed out of Arnold's efforts.[5] William Bement succeeded so well in designing a line of machine tools for the Lowell Machine Shop that he left for Philadelphia, where he established one of the country's leading machine tool firms. Training at Gay and Silver, a leading textile machinery firm, provided capabilities that Frederick Howe used to mass-produce firearms. For Arnold, Bement, and Howe textile machines focused attention on production problems that applied to other eastern industries. Other textile machinists applied skills in machine design and construction to machine tools, locomotives, firearms, sewing machines, screw making, and many other sectors.[6]

Commodities developed for textile production helped mechanization elsewhere, especially waterpower equipment and machine tools. Water turbines sold widely. E. C. Kilburn sold turbines and shafting mostly to textile mills but also to paper mills, agricultural equipment firms, and flour mills. A number of textile machine firms sold machine tools, including Kilburn, Lowell, and Gay and Silver. Some inventors contracted to have textile machinery firms make their machines, such as Joseph Woodbury, who in 1849 contracted with Kilburn to build "three of my patent Planing Machines" at $725 per machine with the stipulation that they be "like the one you are now building for me . . . except a little more perfect finish."[7] Reflecting on the limits of card wire, Ichabod Washburn, a wool machine and

lead pipe producer in the card-making center of Worcester, invented wire-drawing machinery. By 1831 he perfected his techniques and began production on a small scale, employing 14 workers to produce $8,760 in wire and another $4,150 in machinery. He came to dominate the local and national card wire business and then applied his techniques to telegraph wire, hoopskirt wire, piano wire, screws, and other products. In 1860 he led Worcester's wire-drawing firms, which produced 58 percent of the nation's total wire output.[8]

Diversifying textile machinery firms moved into other industries. Although many specialized after 1830, others spread into products as diverse as machine tools, turbines, agricultural machinery, paper machinery, and locomotives. Slowing growth of textile machinery output, underutilized plants, and advantages of substantial design and production capabilities were sufficient incentives to diversify. Locks and Canals diversified before its machine contracts for Lowell mills slowed around 1840. It moved into distinct textile machines for printing and woolens, machine tools, shafting, steam engines, boilers, cotton gins, castings, turbines, hydraulic presses, hydrants, sugar mills, sewing machine needles, iron bridges, pumps, paper mill machinery, and locomotives.[9]

Diversification had its trials and tribulations. In 1838 Locks and Canals contracted with a southern physician to make and sell a cotton gin he had designed. Working with new agents in new areas proved difficult. Dr. Jones, who wrote incessantly, proved a major absorption of managerial time, as treasurer Patrick Jackson plaintively noted: "The fact is the Doctor is so voluminous a correspondent, that all the time I can devote to Cotton Gins, is devoted to reading, analyzing & answering his letters."[10] Faced with problems of little demand, low markups, and patent litigation, Locks and Canals abandoned cotton gins in the early 1840s. The line of special-purpose lathes and other machine tools designed by Bement sold well, yet after Bement left, the Lowell Machine Shop greatly reduced its machine tool sales. Plagued with its failures and its successes alike, Lowell would concentrate on textile machinery after 1865.

Amoskeag rivaled Locks and Canals in its breadth of product line. Its 1860 Manchester city directory ad, featuring its fire engine, read: "The Amoskeag Mnf'g Co. are manufacturers of Steam Fire Engines, Locomotives, and Stationary Steam Engines, Boilers, Cotton and Woollen Machinery, Tools, Turbine Wheels, Mill Work, and Castings, of every description." Other firms specializing in textile machinery spread into turbines (Kilburn, Hadley Falls), pumps (Fales and Jenks), machine tools (Mattewan, Kilburn, Putnam Machine Company), steam and fire engines (Lawrence Machine Shop, Mattewan, Kilburn, Putnam), printing (Lawrence), paper machinery (Lawrence, Hadley Falls), shoe and leather

machines (Lawrence), sugar mills (Matteawan), woodworking machinery (Putnam), shafting and gearing (many firms), and locomotives (Mason, Lawrence, Danforth, Rogers). Many products were heavy machines, for which textile machines prepared machinists well. Mason's capacity to cast and machine mules 60 feet long with 1,088 spindles surely aided his production of locomotives.[11] Some firms shifted their central business. Kilburn moved into turbines. Worcester firms entered machine tools. In Fitchburg Putnam moved into steam engines, machine tools, and woodworking equipment. By the 1840s Rogers concentrated largely on locomotives.

Technological principles developed for textile production spread through more diffuse means. One of most important methods was Wilkinson's industrial lathe. In his "Reminiscences" Wilkinson claimed that his lathe was "worth all the other tools in use, in any workshop in the world, for finishing [e.g., machining] brass and iron work." He also suggested why it had such universal importance: "The weighted slide, the joint made by gravity, applies to planing, turning, and boring of metals of every kind, and every way."[12] An 1848 U.S. Senate report of the Committee on Military Affairs pointed to the lathe's importance after Wilkinson's patent expired in 1812: "Being thus left open to general use, an invention so vastly important in its character could not fail to be sought after, not only by the public at large, but also by the agents of the government engaged in the fabrication of arms of various descriptions; and hence we find that the guage [*sic*] and sliding lathe was early introduced and made use of in all of the arsenals and armories of the United States." Noting that Wilkinson was the "true and undisputed author" of the lathe, that it was "indispensable" in making firearms, and that public armories used nearly 200 lathes based on the invention, the committee recommended a reward of $10,000 for Wilkinson, which he received.[13] In 1861 Zachariah Allen pointed to its broad significance: "It has to this day proved the most effective tool placed within the control of mankind for shaping refractory metals and for accomplishing the triumph of mind over matter. The slide engine is employed in the great machine shops of America and Europe."[14] The lathe spread modestly by sale of machines or patent rights. Others observed it, including Jacob Perkins; Wilkinson speculated that Perkins used it to engrave banknotes. Wilkinson sold castings to the Springfield Armory, which adapted it to barrel turning in 1818. Wilkinson's workers spread it in Rhode Island, Massachusetts, and New Hampshire.[15]

Daniel Webster was said to have singled out Amos Whittemore's automated card-clothing machine by commenting that "it seemed to be more nearly endowed with human intelligence than any other machine ever invented."[16] Whittemore's machine was one of the first to perform a series of operations by suit-

ably arranging cams of appropriate shapes along a drive shaft. The principle applied widely. A British user of Whittemore's patent described its effects: "The application of curvilinear projections or cam pieces has since been extensively employed for giving intricate motions in many other machines invented during the last fifty years."[17]

Aza Arnold's differential gear embodied a third widely important technological principle. This gear solved the problem of varying the relative rotation speeds of two parts in desired fashion. Needed on roving frames to slow down bobbin rotation as the bobbin filled, it would be applied to a wide range of mechanical activities, including the differential gear of automobiles, which allows wheels to rotate at different speeds when going around curves. The eminent British engineer Andrew Ure used it as an example of an elegant solution to a general mechanical problem.[18]

Through such mechanisms the textile sector might have led innovation in the U.S. economy. George Gibb suggests as much: "For a considerable part of the 1813–53 period the manufacture of textile machinery appears to have been American's greatest heavy goods industry . . . From the textile mills and the textile machine shops came the men who supplied most of the tools for the American Industrial Revolution. From these mills and shops sprang directly the machine tool and the locomotive industries."[19] The claim is plausible, for the textile sector was the point of origin of the American industrial lathe, a point of entry of the British planer, and a locus developing iron construction, power transmission, systematic design, and improved machine tools.

Measuring leadership is a challenge. One indicator is whether those trained in textiles innovated more widely than those trained elsewhere innovated in textiles, which can be examined for major innovators. Fifty-seven were trained in the textile sector (some in combination with other sectors), one-fifth of all innovators with patents through 1865 (table 9.1). The share was far greater than the share of textile occupations in the labor force, but it does suggest that textiles was not the only leader. All but one textile innovators were trained in the textile sector. Sixty-three percent of those with textile training innovated outside the textile sector, including 36 percent of sewing machine, leather, and other apparel innovators, 32 percent of metalworking innovators, and 20 percent of water and steam power innovators. Because some textile innovations, including those of Whittemore and Arnold, also applied outside textiles, textile leadership was greater yet. The share who innovated in other sectors doubled over time. Only three-eighths of those trained in textiles innovated in other sectors by 1835, including Oliver Evans's and Zachariah Allen's steam engines. After 1835 three-quarters innovated in other sectors. Textile-trained innovators first invented at home then spread their knowledge much more broadly.

Table 9.1. Leadership by Textiles

	Textile-Trained Innovators	Share of Innovators with Textile Training (%)	Distribution of Innovations by Textile-Trained Inventors (%)		
			All	1790–1835	1836–65
Textiles	21	95.5	36.8	63.2	23.7
Apparel	5	35.7	8.8	0	13.2
Craft-based	3	10.7	5.3	5.3	5.3
Metalworking	12	32.4	21.1	10.5	26.3
Agriculture	1	3.4	1.8	0	2.6
Instruments and mechanisms	5	11.6	8.8	0	13.2
Transportation	2	5.4	3.5	0	5.3
Chemical and electrical	2	6.7	3.5	5.3	2.6
Power	6	20.0	10.5	15.8	7.9
Construction	0	0	0	0	0
All	57	20.2	100.0	100.0	100.0

Sources: See table 4.10.

The breadth of textile leadership is indicated by the sectoral distribution of textile-trained innovators. Karl Marx divided the machine into working parts that came in contact with the material, parts to transmit power, and the motor mechanism to supply power. Textile-trained innovators developed each part. Some applied textile knowledge to operations shared with textiles. As has been seen, textile machinists were principal inventors of the sewing machine, including Elias Howe, John Bradshaw, and John Bachelder. Gordon McKay, the superintendent of the Lawrence Machine Shop, formed the company that applied the sewing machine to shoe bottoming. Machine tool innovations by Wilkinson, James Brown, and Ira Gay had wide significance. Three of the greatest midcentury machine tool innovators, Joseph R. Brown, Frederick Howe, and Francis Pratt, were trained as textile machinists. Howe's training in Gay's shop, which reportedly used turret lathes, supplied knowledge that he used to develop turret lathes and other means to mass-produce firearms.[20] Production prowess learned in the textile sector enabled firms to diversify, including locomotive innovators Matthias Baldwin, Charles Danforth, William Mason, and Thomas Rogers.

Transmission mechanisms inherently applied more widely, as Whittemore's cam mechanism and Arnold's differential gear illustrate. Gearing and shafting improvements spread to other sectors, including Moody's use of belting instead of metal gearing for the drive shafts of mills.[21] The motor mechanism applied wherever mechanical power was used. Turbines spread from textile mills to many other sectors through sale, the movement of mechanics, and publications such as

James Francis's *Lowell Hydraulic Experiments.* Francis, Uriah Boyden, and E. C. Kilburn all were trained in textiles. While not the originator of the turbine, the textile industry was its principal locus of development and dissemination in the United States. The industry also advanced steam power development through the steam mill movement, which used sophisticated engines in coastal mills, led by Slater's steam mill superintendent, Charles James. The textile industry became the biggest single market for the Corliss engine in the 1850s.[22]

Patent records can be used to document interindustry mobility when inventors took out patents that crossed industry lines, as Wilkinson did when he received patents for canal locks and packing cotton. Although his patents did not share particular technological principles, they were related because general mechanical skills and inventive experience applied to other sectors of the economy. Textile inventors patented widely. Evans's carding machine was his first major invention, and while its mechanisms differed greatly from those of his flour mill or engine, it was the occasion for learning how to conceive inventive problems and master knowledge that supplied solutions. The links often were roundabout. Corliss was trained in textile mills, where he learned of thread manipulation methods that he applied in a sewing machine. The futile effort to sell his machine in Providence landed him a job in a steam engine firm. Thirty-two major innovators began with textile inventions, including Matthias Baldwin and Ross Winans in locomotives, James Gibbs in sewing machines, Frederick Howe and Christopher Spencer in firearms, and Stephen Wilcox in boilers; one-third innovated principally in other sectors. By contrast, only two of 23 textile innovators first invented in other sectors, and one of them, James S. Brown, began with a slide rest used to make textile machinery. A sample of 127 textile inventors reinforces these conclusions. Of those patenting in more than one category, two-thirds began inventing in textiles. Many patented in related areas, including Kasmir Vogel, who invented the button-sewing machine.

Because textile mechanization originated techniques, formed inventive practices, and trained producers who spread these techniques, it was one point of origin for American mechanization.[23] Did it lead overall mechanization before the Civil War? Joseph Roe put the question in an interesting light when he wrote, "As the gun industry developed the interchangeable system, so the cotton industry developed the American general machine tool."[24] If he is right, there were at least two leading industries. As table 9.1 indicates, the textile industry was significant for apparel industries, gearing improvements, waterpower, and machine tools. But in many sectors innovators had little background in textiles. Gibbs's claim that textile machinery constituted the leading antebellum heavy industry and

the source of the machine tool and locomotive industries is exaggerated when applied to the whole country, though its role in New England was greater. It also played a larger role before 1830, when other early industrializers were only starting to advance.

Many industries developed through largely independent processes through 1835, and each led in parts of the economy. Firearms clearly did. If important leaders had to be large, then the peacetime firearms industry was a poor candidate. Whereas in 1860 the textile industry produced almost 12 percent of manufacturing value added, firearms was small, with only one-quarter of 1 percent. Yet its claims to long-run leadership are strong. Nathan Rosenberg and David Hounshell documented a direct line of mass production leading from firearms to automobiles.[25] Firearms affected the broader economy in a series of ways. Gunsmiths, one center of mechanical expertise in the Colonial economy, applied their skills in many industrializing sectors. John Fitch, Robert Fulton, and Amos Whittemore all had gunsmithing experience that may have supported their innovation. This is not unlike the case for traditional clock makers who used skills in other sectors, including Fitch, Joseph Brown, the steamboat innovator Daniel Dod, and the locomotive inventor Phineas Davis.

The key question is whether innovations in the firearms industry supported innovation in other sectors. Interchangeable-parts production was the biggest effect, and the sewing machine was the most important recipient. Firearms played a causal role in the two most advanced cases. To mass-produce Willcox and Gibbs machines, Joseph Brown, despite an unparalleled record in precision work, needed several years to introduce interchangeable-parts methods. Even in the leading center of Providence, purchased lathes were so inaccurate that Brown had to rebuild them. He learned from firearms producers and invented to augment their techniques. Occasioned by Frederick Howe's encouragement to find an accurate means to cut twist-drill bits, Brown invented the universal milling machine to make sewing machines and Howe's firearms, which developed into an indispensable tool room machine. Brown's turret lathe, also used to make firearms and sewing machines, became a central mass production machine tool.[26] Firearms developments hence shaped sewing machine production and wider machine tool usage.

Wheeler and Wilson also imported armory methods. In 1863 *Scientific American* described its machine tools, gauges and testing procedures, remarking that "such a complete and perfect principle of accuracy . . . has never fallen under our notice before." The apparent miracle required the organized transfer of techniques from New England firearms factories. In 1856 William Perry, a Colt

contractor, became superintendent of Wheeler and Wilson's Bridgeport factory. Perry, working with two Robbins and Lawrence contractors, Joseph Alvord and James Wilson, applied and improved armory practice to make sewing machines with largely interchangeable parts.[27]

Firearms had considerably wider effects. Aaron Denison used techniques he had studied at the Springfield Armory to mass-produce watches; the armory-trained Ambrose Webster organized the machine shop. Blanchard's pattern lathe spread to lasts, oar handles, ax handles, and much else. Firearms educated important hardware producers, including Eli Whitney Blake, the nephew of Eli Whitney. Blake ran Whitney's firearms factory until the 1830s, when the contracting system declined. Blake and his brothers then developed locks and other hardware before devising a stone-crushing machine for paving roads. Firearms' most general effect was the spread of machine tools originated for firearms production, led by Brown and Sharpe and Pratt and Whitney.

The experience of workers at Robbins and Lawrence and at Colt well illustrates the spinoffs. Both firms trained machinists who left to make machine tools, hardware, screws, textile machinery, and other machines. Many made sewing machines using armory techniques (table 9.2). Their invention concentrated on machine tools and forging but extended widely in metalworking and metal products. At least for these sectors of the economy, firearms was a leading industry. Compared to textiles, firearms generated fewer innovators in other sectors, and they were active later in the period. The argument for leadership from the firearms industry focuses on metalworking methods used in many industries by 1865, on innovations in sewing machine and watch production that had major commercial impact by 1865, and on the trajectory of changes leading to mass-produced bicycles and automobiles in the next half-century.

Other early industrializers also had cross-industry effects. Clock makers continued their long tradition making precision mechanisms. Joseph R. Brown used his skill to make precision measuring devices, such as vernier calipers, gauges, and rulers, which eased his entry into interchangeable-parts production. James J. Clark invented and made telegraph instruments. Other clock makers developed scientific instruments. Woodworking improvements were widely used, beginning with Blanchard. Elisha Root had superintended the preeminent U.S. ax-making factory, where he used pattern lathes to make handles and developed drop-forging and machining methods to make ax heads. He used both techniques in the Colt Armory. R. Hoe applied metalworking skills to saw making, conducted experimental work, introduced planers and other machine tools, and trained Isaac Singer and other machinists. Spinoffs from early industrializers were externali-

Table 9.2. Spinoffs from Two Firearms Firms

	Other Production	Other Inventions
Robbins & Lawrence		
Joseph D. Alvord	sewing machines	grinding; sewing machines
Charles Billings	forging; screws; sewing machines	drop forging
Frank Chase	machine tools; railroad mechanic	
George Fairfield	sewing machines; screws	screw making
Frederick Howe	machine tools, tools	machine tools
George Hubbard	railroad; textile machinery, machine tools	
Richard Lawrence		machine tools, drop forging
S. E. Robbins	sewing machines	
Henry Stone	machine tools; sewing machines	machine tools
Rollin White	textiles	
James Wilson	sewing machines	
Colt Manufacturing		
Charles Billings	forging; screws; sewing machines	drop forging
E. P. Bullard	machine tools	machine tools
Samuel Colt	telegraph	
Hezekiah Conant		thread dressing and winding
Asa Cook	screw and bolt machinery	screw and bolt machinery
George Crompton	weaving machinery	power looms
A. F. Cushman	lathes	lathe chucks
George Fairfield	sewing machines; screws	screw making
James E. Gleason	gear cutters	
William Hicks	engines	engines, sewing machines
Henry Leland	machine tools, sewing machines, automobiles	machine tools, automobiles
George Lincoln	machine tools	Lincoln miller
William Mason		looms; steam pumps; bridges
William H. Perry	sewing machines	
Francis Pratt	machine tools	machine tools
Charles B. Richards	mechanical engineer; steam engines	steam indicator
Elisha Root		machine tools, drop forging
Christopher Spencer	textile machinery; forgings; machine tools	silk-winding; forging; machine tools
Amos Whitney	machine tools	

Sources: Roe, *English and American Tool Builders,* 173–201; Guy Hubbard, "Development of Machine Tools in New England," *American Machinist* 59 (1923): 1–4, 139–42, 241–44, 311–15, 389–92, 463–67, 541–44, 579–81, 919–22; 60 (1924): 129–32, 171–73, 205–9, 255–58, 271–74, 437–41, 617–20, 875–78, 951–54; 61 (1924): 65–69, 195–98, 269–72, 313–16, 453–55; Hounshell, *From the American System to Mass Production,* 68–82; *Dictionary of American Biography*; *Mechanical Engineers in America Born prior to 1861: A Biographical Dictionary* (New York: American Society of Mechanical Engineers, 1980).

Note: Some of these effects came after the Civil War.

ties that advanced innovation in a wide range of industries. The claim that a single industry led is not readily supported, if only because many did so.

The Steam Engine as a General-Purpose Technology

In commenting on Marestier's steamboat report, the French Royal Academy focused on "a new kind of useful mechanical power" that affected "a large number of other branches." The steam engine was the archetypal general-purpose technology (GPT). For Marx it had "universal technical application," which Watt's genius recognized.[28] Because of its universality, the engine's dynamic interlinked with those of many industries. It differed from textiles because its evolution affected many industries directly and the evolution of engine-using industries affected it. Positive feedbacks affecting many industries underlay engine development, whereas the textile industry's spinoffs to other industries rarely benefited it. Perhaps the engine uniquely "accelerates the general progress of invention" because it had a universality that textiles or firearms lacked.

According to one interpretation, three attributes distinguish a general-purpose technology from special-purpose technologies. When it is introduced, a GPT has considerable scope for improvement, so that its diffusion typically takes longer than a special-purpose technology that needs less adaptation to different uses. Further, a GPT meets many needs and has major effects. Finally, a GPT evolves through innovational complementarities; innovation in the GPT, by reducing its price or improving its quality, supports innovation in sectors using it, and innovation in these sectors supports continued innovation in the GPT.[29] Harking back to the young Schumpeter, a leading sector, typically understood as a key input, can become an "engine of growth" that propels the whole economy in a decades-long process. Antebellum GPTs included engines, steamboats, waterpower, railroads, iron working, and telegraphs.[30]

The steam engine displayed each characteristic. The U.S. engine in 1800, hobbled by basic deficiencies in its design and construction, diffused slowly. Even in 1870—a century after Watts's invention and 65 years after the first successful usage in the United States—steam provided only half of the power in U.S. manufacturing. By 1838 engines found considerable usage to make lumber, textiles, machinery, sugar, flour, iron, iron castings, wood products, hardware, liquor, leather, paper, publications, and cordage.[31] Innovational complementarities abounded. Improved engines for one industry benefited others, such as when horizontal steamboat engines found stationary uses or cutoffs designed for textile markets proved valuable for rolling mills. The Corliss engine met the need of complex

manufactures for precision and regularity of motion, thus enabling sophisticated urban production to grow, with attendant agglomeration economies affecting many industries.[32] Positive feedbacks also existed within industry networks linking textile and textile machinery firms or between publishing firms and press makers. The difference was that improved engines for one industry also secured sales in other industries.

Engines also led through spillovers of production and design capabilities. Employing over half of machinery industry workers in 1860, firms that made durable, precise engines used machinery capabilities to make a wide range of products, often combining engines with castings, such as the 1841 Pittsburgh firm advertising: "All kinds of Steam Engines and Boilers, Mill Irons and Gearing, and Castings of all kinds, made to order." Firms integrated into machine tools, selling a growing variety. In 1850 a Boston engine maker offered: "Machinists' Tools, of all Descriptions, including Turning Lathes, of sizes varying from 6 feet to 50 feet in length . . . Planing Machines, varying from 2 to 60 feet in length, Boring Mills, Vertical and Horizontal Drills, Slotting Machines, Punching Presses, Gear and Screw Cutting Machines, etc."[33]

Engine makers used design skills to invent widely. Eighteen percent of major innovators were trained in engines and navigation before they innovated. Utilizing their background, they concentrated on steam engineering, receiving 54 percent of innovations in transportation, 43 percent in power, and 33 percent in construction, often linked to railroads.[34] Convergences within steam engineering spread technological change between sectors, much as improved stationary and boat engines fed off each other. The locomotive was the most important new use of engines before the Civil War, and engine makers were prominent inventors and producers. The Swedish émigré John Ericsson brought hot-air and screw propeller inventions and in the United States developed steam fire engines and a design for steam vessels that was the basis of the Civil War Monitor. Samuel Morey's gas combustion engine developed principles that later bore fruit. Convergences also were decisive in developing the steam-hoisting machine, steam-dredging machine, and pumping engine, most notably the Worthington pump. Helped by knowledge of engine and boiler design acquired while developing a steamboat for canal navigation, Henry Worthington first developed a steam pump to automate boiler feeding, which came to be widely used for boilers on steamboats and stationary engines. Worthington then addressed urban water supply and developed a simple, relatively inexpensive, but highly efficient direct-acting steam pump, first used in the Savannah, Georgia, waterworks in 1854. After the war the Worthington pump became "a virtually indispensable means of serving an

endless variety of industrial needs for the handling of water and other liquids," including breweries, oil refineries, and much else.[35] Its function—applying power to drive a liquid-moving plunger—led to fundamental differences in design, including slower piston speeds.

Randomly sampled engine and navigation inventors provide evidence about the direction of spinoffs. They received 48 percent of their patents for steam engine and navigation improvements and 14 percent for railroad, boiler, and steam and water changes. One quarter of inventors who gained use for engine or steamboat patents also invented pumps, including Birdsall Holly, who rivaled Worthington in postwar urban waterworks. Two-fifths invented more widely. Some inventions complemented engines in the same production systems. Metalworking inventions, such as Corliss's gear cutter, boiler tube forming machine, and casting improvements, enhanced engines and boilers. New gearing improved power transmission, and new machines utilized this power to grind, cut, roll, and drill. More numerous were inventions that used technical principles of engines or their use. Engine inventors developed mechanisms to pump oil and other liquids and to control the flow of gas in lighting. Other crossover inventions were less directly related to the engine, but many shared convergent principles. Jordon Mott, for example, developed casting techniques to make stoves that he applied to make railroad car wheels. Engine invention and usage fostered invention elsewhere. Among crossover inventors steam engine and navigation patents preceded others twice as often as others preceded them, and almost two-thirds of those who gained use for engines received other kinds of patents, compared to one-third for those without such usage.

How important was steam engine leadership for U.S. technological development? The engine enabled innovation among engine users and supported other steam engineering innovations. Expanded usage trained machinists, who invented and perfected inventions. Growing steampower in cities, where inventors were common and more prolific, added to inventive activity. The engine played a relatively larger role in the least-mechanized regions, the South and the West, helping to transport goods and utilize agricultural, mining, and timber resources. Engine making was vital to the Mid-Atlantic region, though New England also made sophisticated stationary engines.[36]

Yet one cannot attribute the great growth of steam-powered production to the engine alone because the expansion also rested on advances in engine-using sectors and production capabilities, much of which would have occurred in the engine's absence. Advances in many sectors depended on their own dynamics more than on the presence of the engine. In textiles the core dynamic was grounded in waterpower, and the application of steam power barely altered the dynamic. The

very reason for the engine's universality—that it applied in virtually all sectors of production and navigation—also separated it from particular applications. It could power saws, textile machines, and flour mills, but the technologies of sawing, weaving, and milling were outside it. Separated from the actual transformation of materials—from the "working" machine that Marx saw as central to modern industry—engine inventors concentrated on steam technology, not on developing sawmills, textile factories, or flour mills. Although the engine did enable innovation in engine-using sectors, knowledge in the using sector was required and not always present. Engines spread over much of the world in the nineteenth century, but extensive invention in engine-using sectors did not.

Furthermore, practical engines and machines using them rested on improved machine-making capabilities, which evolved largely outside the engine industry. Accurate engine lathes had outside roots in both England and the United States, and engine makers adopted them from the 1820s. The metal-planer, too, had other purposes. Practical engines required adequate machine tools, and the belated spread of machine tools slowed engine diffusion. The presence of machine-making capabilities helps explain why the United States became an engine producer, unlike many places that were simply engine consumers. Hence, leadership by the engine sector should be interpreted as a joint product of innovations in engines, engine-driven equipment, and metalworking capabilities. GPTs became such by relying on innovations that were independent of them.

The relation between the training of major innovators and the content of their innovation illuminates the extent and direction of leadership by early-industrializing sectors. Those trained in the six sectors constituted 56 percent of all innovators. They innovated disproportionately in their own industry, ranging from 65 percent in printing to 9 percent in woodworking (table 9.3). Early-industrializing sectors also benefited from spillovers from those trained in other early sectors, ranging as high as 42 percent of woodworkers' innovations. The leading character of early-industrializing sectors is indicated by the fact that 44 percent of the innovators with backgrounds in one of them innovated in other sectors, but only 22 percent of innovators in early-industrializing sectors had not been trained in these sectors.[37]

Early-industrializing sectors had an uneven impact on innovations elsewhere. They exercised considerable leadership in apparel (led by textile-trained workers), machine tools (led by textiles, firearms, and clocks), and railroads (led by steam engines and boats). They had modest impact on science-based sectors (electricity and chemicals), agriculture, and construction. Moreover, their importance was geographically uneven. Innovators in the five particular industries

Table 9.3. Innovation by Sector of Training (percentages)

Sector of Innovation	Textiles	Firearms	Printing	Clocks	Wood-working	Steam Engines and Boats	Any Early Industry	Other Inno-vators
Textiles	**36.8**	6.5	0	8.3	6.1	2.0	13.3	0.8
Firearms	7.0	**51.6**	0	0	9.1	4.0	11.4	4.8
Printing	1.8	0	**65.0**	0.0	15.2	0	8.2	1.6
Clocks, etc.	1.8	3.2	0.	**25.0**	6.1	0	3.8	6.5
Woodworking	3.5	3.2	5.0	0.0	**9.1**	0	3.2	0
Steam engineering	8.8	12.9	5.0	16.7	6.1	**42.0**	16.5	8.1
Early industries	59.6	77.4	75.0	50.0	51.5	48.0	**56.3**	21.8
Machine tools	7.0	6.5	0	8.3	0	2.0	3.2	0.8
Apparel	8.8	0.	5.0	0	3.0	4.0	5.1	4.8
Other power	1.8	0	0.	8.3	6.1	6.0	4.4	3.2
Railroad	3.5	0	5.0	8.3	6.1	18.0	7.6	6.5
Science-based	3.5	0	5.0	8.3	6.1	4.0	4.4	18.5
Agricultural	1.8	0	0	0.	6.1	0	1.9	21.0
Other	14.0	16.1	10.0	16.7	21.2	18.0	17.1	23.4

Sources: See table 4.10

Note: Each column refers to a locus of training. The cells are column percentages, shares of each innovation type among innovators with a particular mode of training. For example, 36.8 percent of the 57 innovators trained in the textile sector also innovated in that sector. Innovators could have background in more than one sector, such as carpenters who were also trained in textile machinery. As a result, columns cannot be summed to assess the collective importance of these backgrounds. "Clocks, etc." includes locks, scientific instruments, and other instruments. The number of trainees was 57 in textiles, 31 in firearms, 20 in printing, 12 in clocks, 33 in woodworking, 50 in steam engines and boats, and 158 in any early-industrializing sector.

made up two-thirds of New England's innovators but less than one-third for the rest of the country. Two-thirds of those trained in textiles and three-quarters of those trained in firearms were from New England. Steam engineering concentrated in the Mid-Atlantic regions.

Hence, early-industrializing sectors led the development of other sectors, but they did not lead innovation throughout the economy. No single sector predominated. Their effects on other sectors concentrated later in the period. Furthermore, they were also vital to forming technological centers, without which their leadership would have been fundamentally curtailed.

Technological Centers

How did innovators learn about technologies in other industries when their industries of training typically did not provide such knowledge? Movements among

occupations and contacts in families, neighborhoods, clubs, and churches could provide the information. Technological centers supplied an essential structural mechanism because technological occupations and mechanicians held universal knowledge and means to learn about many industries.

Innovation by technological occupations was significant in their industries of training and even more central outside those industries (called "internal" and "crossover" innovation, respectively). Among major innovators machinists dominated internal innovation in textiles, printing, and steam engineering, with as much as 81 percent of internal innovators (table 9.4). Engineers and applied scientists were significant in steam engineering and outside the six early sectors. Occupations with less universal knowledge innovated in clocks, firearms, woodworking, and printing as well as in agriculture, apparel, and some crafts. Machinists were equally central as crossover innovators, and those trained as engineers and applied scientists in each sector were more important as crossover innovators than as internal innovators. Other occupations contributed less to crossover innovation, with shares from none to two-fifths.

Mechanicians constituted two-fifths of internal innovators in steam engineering, firearms, and other industries. They had a greater effect among crossover inventors, making up at least two-fifths of innovators with every form of training except woodworking. Those with universal technological knowledge—combining mechanicians and technological occupations—constituted from 33 to 95 percent of internal innovators, and they made up at least 76 percent of crossover innovators for every mode of training. Innovators did learn through other means. U.S. occupational mobility was high, and some inventors trained in early sectors then moved into occupations in which they innovated. When they are considered, those without universal knowledge who innovated outside their industry of training shrunk to only 3 of the 158 innovators trained in early sectors and 10 of 123 innovators who lacked such training. Learning in technological centers was central to crossover innovation.

Whether typical inventors mirrored major innovators in crossover invention can be evaluated through a survey of all patents for post-1835 inventors in the dozen technology types examined so far in the book. The 1670 inventors with known occupations received over 8,000 patents. Fifty-eight percent had technological occupations, about 76 percent of whom were machinists. Machinists included at least three-tenths of inventors in all but three sectors (table 9.5). In two of the three, telegraphs and bridges, applied science and inventive occupations led the way. Technological occupations made up half or more of all inventors in every industry but clocks and firearms, in which crafts had significant mechanical

Table 9.4. Innovators and Kinds of Learning (percentages)

	Textiles	Firearms	Printing	Clocks	Wood-working	Steam Engines and Boats	Other Training
Internal innovation							
Machinists	77.3	50.0	76.9	0	33.3	81.0	35.4
Engineers and applied science	0	18.8	7.7	0	0	33.3	37.8
Other occupations	22.7	37.5	23.1	100.0	66.7	9.5	32.9
Mechanicians	13.6	43.8	15.4	33.3	0	57.1	47.6
All with universal knowledge	86.4	68.8	76.9	33.3	33.3	95.2	72.0
No universal knowledge	13.6	31.3	23.1	66.7	66.7	4.8	28.0
Crossover innovation							
Machinists	85.7	66.7	57.1	66.7	76.7	75.9	19.5
Engineers and applied science	20.0	20.0	14.3	11.1	10.0	37.9	46.3
Other occupations	5.7	26.7	28.6	22.2	20.0	0	39.0
Mechanicians	48.6	40.0	85.7	66.7	13.3	55.2	63.4
All with universal knowledge	97.1	93.3	100.0	100.0	80.0	100.0	75.6
No universal knowledge	2.9	6.7	0	0	20.0	0	24.4
Occupation change	0	6.7	0	0	13.3	0	0

Source: See table 4.10.

Note: Cells are shares of internal and crossover innovators (for the top and bottom panels) with a particular kind of training; for example machinists made up 77 percent of internal innovators with a textile background. Innovators with training as machinists and engineers were included in both rows, so that the total of both groups and other occupations could exceed 100 percent. Internal innovators had prior training within the sector of innovation. Crossover innovators had training in one sector but innovated in another. Each column except the last identifies those trained in an early sector; altogether 158 innovators had such training. The last column examines those without training in any of the six early sectors. "All with universal knowledge" includes machinists, applied science and inventive training, and mechanicians. Innovators often fell in more than one of these groups so that the "with universal knowledge" row need not equal the sum of the rows making it up.

knowledge, and railroads, in which carpenters and others led nonlocomotive invention. Technological occupations averaged 2.6 patents in the surveyed category (called "internal patents"), above the average 2.0 patents for other occupations. Only in firearms and clocks did other occupations patent more internally.[38]

Centers also led in crossover patenting. Technological occupations used cross-industry knowledge to invent more outside the surveyed industry. Their 3.1 crossover patents for all categories were almost twice as many as those of inventors from other occupations; altogether they received 72 percent of such patents. Early

Table 9.5. Invention and Technological Centers, 1836–1865 (percentages)

	Machinery			*Applied Science and Invention*			*All Technological Centers*		
	Inventors	Internal Patents	Crossover Patents	Inventors	Internal Patents	Crossover Patents	Inventors	Internal Patents	Crossover Patents
Textiles	51.1	62.9	46.9	4.8	4.4	13.8	55.9	67.3	60.7
Firearms	30.4	28.7	51.4	12.0	8.1	14.1	42.4	36.7	65.4
Printing presses	43.5	61.4	62.4	18.8	10.9	26.9	62.4	72.3	89.3
Clockmaking	18.6	16.6	38.5	4.3	2.1	19.2	22.9	18.6	57.7
Woodworking	45.3	54.4	62.1	4.7	5.0	18.6	50.0	59.5	80.7
Steam engines	52.2	60.6	64.3	21.2	19.7	21.3	73.5	80.3	85.6
Machine tools	68.7	80.6	62.6	9.6	6.9	9.1	78.3	87.5	71.7
Sewing machines	56.7	64.6	64.8	11.3	9.5	11.8	68.0	74.0	76.7
Bridges	8.2	8.3	12.9	55.1	57.1	49.1	63.3	65.5	62.1
Railroad	37.2	45.1	48.7	11.5	12.0	12.3	48.7	57.1	61.0
Telegraphs	13.6	7.6	12.7	45.5	66.9	45.2	59.1	74.5	57.9
Reapers	50.3	57.7	53.1	7.9	13.2	21.5	58.2	70.9	74.6
All	43.9	51.0	54.1	13.7	13.0	18.0	57.5	64.0	72.1

Sources: Edmund Burke, *List of Patents for Inventions and Designs, Issued by the United States, from 1790 to 1847* (Washington, D.C.: J. & G. S. Gideon, 1847); U.S. Patent Office, *Annual Report of the Commissioner of Patents* (Washington, D.C., 1839–65); U.S. Patent Office, *Subject Matter Index of Patents for Inventions Issued by the United States Patent Office from 1790 to 1873, Inclusive* (Washington, D.C.: Government Printing Office, 1874).

Note: Only inventors with known occupations are included. The internal patent share is the share of patents in the surveyed category (e.g., textile patents among textile inventors) issued to any group. The crossover patent share is the share of patents outside the surveyed category issued to any group. About 56 percent of randomly surveyed inventors had known occupations; their average of 5.1 patents was far above the 2.1 patents of inventors without known occupations. Given the location of inventors without occupations, the actual shares of inventors from technological occupations likely were lower than the table lists. Of inventors with known occupations, 115 were sampled in more than one category and appear in the data for each. When the double counting is eliminated, inventors in all groups averaged 5.0 patents, and had even more technology groups been studied, the average would have fallen more.

industries led in considerable part because machinists and applied scientists who patented in these sectors used knowledge to invent elsewhere.[39]

How did inventors from nontechnological occupations learn about technologies and opportunities outside their industries? Some had knowledge through their occupation, such as firearms managers who delved into machine tools to improve their manufacturing or engine users who improved engines. Mechanics' institutes, the *Journal of the Franklin Institute,* and *Scientific American* provided knowledge to many. Inventors changed occupations or learned from informal interaction with family and community members. Finally, the patent system spread knowledge and formed a mode to appropriate it. About three-fifths of 433 surveyed inventors assigned at least one patent to others. Machinists and engineers were especially adept, but others assigned regularly, including one-half of inventors from nontechnological occupations. The patent system did not overcome the need for learning outside one's industry, but it did provide an avenue to learn from published patents and a mode to appropriate returns.

For many the combination of training in particular sectors and in centers directed invention. Frederick Howe learned in textiles and firearms and from machinists' interactions. His key innovations did not build on particular principles of textile machines, but without textile training he might never have developed machine tools. Elias Howe applied particular textile principles to his sewing machine, but his invention was also informed by mobility among machine shops and generic mechanical design skills. Much the same was true for all major innovators. The various combinations of particular and universal knowledge differentiated the content of innovation, directing innovators toward fields using their training. Table 9.6 lists innovation types in which a group with a particular kind of training had at least a 50 percent greater share of innovations than did all innovators. Among machinists trained in the six early-industrializing centers, for example, only textiles and apparel had a ratio above 1.5; its 1.67 ratio meant that machinists with such training had a 67 percent higher share of textile and apparel innovations than did all innovators. Early-industrializing occupations, taken together, did not meet this threshold for any innovation type for an important reason: they were diverse enough to spread their innovations over wide areas of the economy.[40] Individual industries provided strong direction. Relative to all innovators, those with textile training had 4.7 times as many innovations in textiles, 80 percent more apparel innovations, and 60 percent more metalworking innovations. As expected, innovators trained in steam engines and boats concentrated on steam power, transportation, construction (mostly bridges), and steam applications such as railroads and pumps. Innovators trained outside early-in-

dustrializing sectors concentrated in agriculture and science. The diversity of innovations partly reflected the diversity of training; a more narrowly trained economy would have limited the range of innovations.

The wide applicability of mechanical knowledge is one reason why machinists as a group had no concentrations; their efforts were used in every type of innovation (though relatively less in electricity and chemistry). Engineers and applied scientists had the most distinctive concentrations; they specialized in construction and transportation (especially engineers), electrical, chemical and other science-based innovations (especially applied scientists), and power (both). Innovators from nontechnological occupations concentrated where technological knowledge was greatest: in such instruments and mechanisms as firearms, clocks, and locks and in craft printing, woodworking, and lamp making. Like applied scientists, mechanicians concentrated on science and power.

Technological occupations differentiated the content of innovations among innovators trained in the same sectors (as reading across rows indicates). Among innovators trained in early-industrializing sectors, machinists concentrated in textiles (though they were important in every sector but agriculture and science); applied scientists in transportation, construction, and power; and others in instruments and crafts. Innovators trained in steam engines and steamboats focused on related sectors. Other early industrializers varied considerably. Machinists concentrated on textiles, apparel, printing, and woodworking; applied scientists on power and firearms; and others on clocks, locks, crafts, and textiles. Among those outside early-industrializing sectors machinists concentrated especially in agriculture, applied scientists in science, and farmers in agriculture.

The added knowledge from off-the-job scientific training shaped mechanicians' innovation. Applied scientists focused on construction and science and, secondarily, on power. Mechanicians from machinery and nontechnological occupations concentrated on metalworking but varied greatly in content. Machinists focused on widely applicable casting, machining, and forging techniques, whereas others developed stoves, dental tools, hardware, and pipes. Early-industrializing mechanicians of all backgrounds concentrated on power innovations, but machinists added metalworking, applied scientists construction and transportation, and others instruments. Mechanicians without backgrounds in early industrialization concentrated more on science-based innovations. Nonmechanicians differed greatly, with machinists specializing on textiles and agriculture and others on crafts and instruments.

Similarly, the content of innovation among those trained in technological centers varied with their particular training, demonstrating the importance of

Table 9.6. Innovative Concentration by Type of Training

	All	Machinists	Science and Invention	Outside Centers
All		None	Construction; science; transportation; power	Instruments; crafts
Early occupations	None	Textiles	Transportation; construction; power	Instruments; crafts
Particular	Textiles; crafts	Textiles; crafts	Power; instruments	Instruments; crafts; textiles
Engines and boats	Transportation; power; construction	Transportation; power	Transportation; construction	—
Other occupations	Agriculture; science	Agriculture; construction	Science; construction	Agriculture
Mechanicians	Science; power	Metalworking	Construction; science; power	Metalworking
Early occupations	Power	Power; metalworking	Construction; power; transportation	Instruments; power
Other occupations	Science	Construction; metalworking; agriculture	Science; construction	Metalworking; science
Nonmechanicians	Textiles; agriculture; crafts	Textiles; agriculture	—	Crafts; instruments
Early occupations	Textiles; crafts	Textiles; crafts	—	Crafts; instruments
Other occupations	Agriculture	Agriculture	—	Agriculture

Sources: See table 4.10.

Note: Names of innovation types are shortened; paralleling other tables, "textiles" includes apparel, and "instruments" include mechanisms. Innovative concentration is measured by the index of innovative incidence, which, for a group with a particular kind of training (such as machinists trained in early-industrializing sectors), is the share of any innovation type in all innovations of that group compared to the share of that innovation type among all innovations. Reported innovation types had indices of 1.5 or more and are listed from highest to lowest index. This means that each listed type had at least a 50 percent higher share of all innovations for the group than the share of that type among all innovations. Nonmechanicians in science and engineering professions and in engine and boat occupations outside technological centers were not listed because the number of innovators was too small.

particular paths. Machinists exemplified this trend clearly. Machinists trained in particular early occupations concentrated on textiles and crafts, those trained in engines and boats focused on transportation and power, and those trained outside early industrializers specialized in agriculture and construction (see table 9.6).

The breadth of kinds of training in earlier innovations added to the wideness of later innovation. Had textiles not developed, apparel and metalworking innovations would have been impaired. Had steam engines and boats not evolved, the birth of railroads, pumps, and other steam engineering faced greater obstacles. Had firearms not mechanized, mass production would have been limited in sewing machines and clocks. Without mechanicians scientific and power innovations would have emerged more slowly. In the absence of technological centers innovation might have remained confined to early-industrializing sectors, and even these would have been limited. Centers promoted cross-industry change within existing industries, utilizing industry networks and techniques transmitted from other industries. They also gave rise to wholly new industries, bridging the gaps between potential users and those with needed knowledge. Centers bolstered the leadership of industries and GPTs and added to the number of such leaders, forming an increasingly complex dynamic of cumulative technological change.

Technological Communication and the General Progress of Invention

The transition from nascent industrialization in a few industries before 1825 to the much-widened innovation in 1865 was also a transformation from largely self-contained, industry-specific processes to an integrated dynamic of mutually informing industries. Technological capabilities accumulated within early-industrializing sectors. Technological change accelerated when the capabilities transcended industries.

Capabilities formed in early industrializers led innovation elsewhere in two ways. First, many inventors developed convergent innovations. The railroad was a nested innovation that incorporated simpler, earlier technologies. Schumpeter rightly pointed to its discontinuity when noting, "Add successively as many mail coaches as you please, you will never get a railway thereby."[41] Nevetheless, it built on established techniques, as the British engine-operator George Stephenson learned when he mounted an engine on wheels set on a coal mine's rails.[42] The United States internalized the railroad so quickly partly because it drew on the capabilities of well-established domestic engine makers, steamboat manufactur-

ers, engineers, and heavy-machinery firms. A much wider array of convergent technological principles spread from early sectors to later ones, including universal knowledge of kinematics, friction, and power generation and particular knowledge of woodworking, thread manipulation, and wire making.

Second, innovations such as machine tools and other iron-working techniques complemented technologies particular to an industry.[43] For decades imprecise machining and metalworking methods limited the use of sophisticated techniques, but by midcentury leading shops had adequate machines to bore, turn, drill, plane, and forge. Machine tools became universal inputs indirectly: they were machines to make the machines that ran much of industry.[44] Firearms, axes, engines, clocks, and other sectors prompted machine tool development. Improved machine tools targeted at one industry enabled many other industries to advance, so that sophisticated mechanical innovations could succeed. Textiles and firearms led partly by developing such widely used innovations as Wilkinson's lathe and the milling machine. Such mutually supporting cumulative development of many industries limited the leadership of any one industry.

Early industries and GPTs helped to shape technological centers. An integrated machinery sector formed out of network dynamics in many industries and technologies. Using convergent principles and complementary techniques, practitioners linked industries when commodity sale, occupational change, local communication, publications, or civic organizations spread relevant knowledge. Metalworking methods and principles of product design both were essential to the formation of a machinery center. Common principles and problems existed often enough, but an organized medium to spread knowledge of principles and problems was the step that linked separate dynamics into one center. Organized centers, with regular cross-industry communication, then spread knowledge through occupational and civic channels.

The formation of other centers rested more on noneconomic factors. Infrastructure projects, commonly undertaken by governments, gave rise to civil engineers, including hydraulic engineers who designed and built waterpower systems extending from reservoirs to final usage. Colleges and governments provided much knowledge, personnel, and financing. Mechanical engineers emanated more from machine shops and steamboats, though the navy's engineers contributed.[45] Inventive professions were closely linked to the transformation of the patent system.

Electrical technology relied on scientific advances and scientifically trained innovators; occupations and industries then gave it an economic dynamic. The breadth of electrical innovation manifested the centrality of science. The telegraph industry led—Edison was one beneficiary—yet Thomas Davenport's en-

gine, Charles Page's electric locomotive, and the first arc lights developed in the same period. Electricity was an emerging technological center with uses reflected in the titles of lectures Moses Farmer delivered in 1847: "Electro-Magnetic Engine," "Railroad," "Telegraph," "Submarine Battery" (for blowing up ships), and "Vibrating Magneto Electric Machine . . . so useful in the cure of chronic diseases."[46] Farmer invented along many of these lines, including telegraphs, electric clocks, electric locomotives, electric boiler gauges, batteries, and electrotyping. Others developed medical techniques such as "Compound Magneto Electric Machines" that provided remedies "in all diseases dependent upon a faulty action of the nervous system."[47]

The expansion of centers widened the application of technology. Crossover patenting grew among inventors in early-industrializing sectors. Inventors who patented in such sectors by 1835 averaged 0.9 crossover patents through 1835. The same inventors averaged 1.1 crossover patents after 1835, when centers were forming and deepening. Their post-1835 patenting concentrated on crossover invention; average internal patents fell from 1.5 through 1835 to 0.5 thereafter. Machinists and applied scientists led crossover patenting in both periods. Greater cross-industry transmission of knowledge increased the breadth of invention.[48]

Among major innovators technological centers facilitated the application of knowledge from one innovative sector to many others, as a contrast of early and late innovators documents. As centers grew, so did crossover innovation. The share of technological occupations grew modestly; machinists' share of innovators remained just over 50 percent in each period, and applied scientists grew from 22 to 31 percent of innovators and mechanicians from 39 to 48 percent (table 9.7). Yet the share of innovators trained in early-industrializing sectors who innovated in other sectors nearly doubled, growing from 29 percent before 1836 to 56 percent after (see crossover innovators' shares). Machinists led the way. Before 1836 79 percent of machinists had training in early-industrializing sectors (for some in combination with other sectors), and the share remained at 73 percent after 1835. The share innovating outside their sector of training grew from 26 to 56 percent. Much the same was true for others trained in early-industrializing sectors. The divergence of the locus of training from the content of innovation manifested cross-industry mobility within technological centers.[49]

Technological centers fostered learning among growing numbers of industries. Eugene Ferguson insightfully characterizes innovations at the machinery sector's core: "Innovations in iron-making and in steam-engine building combined to produce an accelerating advance of techniques, augmentation of power,

Table 9.7. Innovators and Crossover Innovation by Training and Period (percentages)

	All	Machinists	Science and Invention	Other
Early innovators				
Shares of all early innovators				
All	100.0	51.5	22.7	31.8
Training in early industrializers	62.1	40.9	9.1	15.2
Mechanicians	39.4	13.6	18.2	12.1
Crossover innovator shares				
All	34.8	29.4	60.0	23.8
Training in early industrializers	29.3	25.9	50.0	20.0
Without early training	44.0	42.9	66.7	27.3
Mechanicians	50.0	22.2	75.0	37.5
Nonmechanicians	25.0	32.0	0	15.4
Later innovators				
Shares of all late innovators				
All	100.0	51.6	31.2	25.6
Training in early industrializers	54.4	37.7	12.6	9.8
Mechanicians	47.9	20.9	28.4	6.0
Crossover innovator shares				
All	44.7	45.0	47.8	41.8
Training in early industrializers	56.4	55.6	74.1	38.1
Without early training	30.6	16.7	30.0	44.1
Mechanicians	50.5	46.7	47.5	69.2
Nonmechanicians	39.3	43.9	50.0	33.3

Sources: See table 4.10.

Note: Shares of all early and late innovators are, respectively, shares of the 66 who innovated before 1836 and the 215 who innovated later. The 51.5 percent of early innovators trained as machinists thus was the ratio of the 34 machinists to the 66 early innovators. Crossover innovator shares are the shares of innovators with any type of training who innovated outside their sphere of training. For early industrializers they innovated outside the early-industrializing sectors in which they were trained (though some also had training in their sector of innovation). For those not trained in early sectors crossover innovators had not been employed in their sector of innovation. The 29.3 percent share of pre-1836 crossover innovators trained in early-industrializing sectors, for example, is the number of such crossover innovators, 12, in relation to the 41 pre-1836 innovators trained in the six early-industrializing sectors: textiles, steam engines and navigation, printing, woodworking, firearms, and clockmaking. The three right-hand columns total more than 100 percent because 22 innovators had backgrounds both as machinists and as applied scientists, 4 among early innovators and 18 later.

and mastery over materials. In this clear-cut example can be seen the interaction of one branch of technology with another. An understanding of this process, whose complexity and impetus toward change are increased exponentially as more and more branches of technology interact, is central to a comprehension of the way in which technological change occurs."[50] Innovations in some sectors reinforced innovation in others. New machine tools improved the quality and

reduced the costs of engines, while engine producers invented machine tools. Textiles, presses, firearms, and woodworking and, later, railroads, harvesters, and sewing machines added to the impetus. Networks in railroads, sewing machines, and other new industries formed more rapidly when machinery and engineering occupations spread knowledge and equipment.

New innovations, in turn, contributed to the body of machinists, applied scientists, and inventive professions who could innovate in other sectors. One-fifth of all machinery industry workers in 1850 made machines that did not exist in 1830, and the share grew to three-eighths in 1860. New sectors added to the ranks of technological occupations. Centers fostered innovation in new industries, which strengthened centers, thus forming positive feedback systems.

Such feedbacks help clarify the evolving character of cumulative technological change. Early on, such change occurred within early-industrializing paths and was limited by their isolation. Capabilities formed along these paths—including the six sectors we have studied and canals, hardware, and casting—led other industries. The vitality of innovation resulted from the fact that many relatively independent processes contributed to accelerating invention; each supplied knowledge and training that shaped particular types of innovations. Late-antebellum development would have been far less revolutionary without such leadership.

After 1835 much technological interaction occurred within technological centers, and leading industries also benefited from developments elsewhere. Acknowledging the mutually reinforcing character of innovation diverts attention from any individual sector and focuses on the complementary character of development.[51] Innovation in industries expanded centers, enabling more cross-industry invention. Centers supported each other; major infrastructural innovations such as the railroad, telegraph, and urban water systems rested on machinery, engineering, and patenting. Technological change was widest when training in particular sectors, GPTs, technological occupations, and civil organizations combined to shape innovations. Particular industries continued to foster the development of others, as textiles supported the invention of the sewing machine and firearms underpinned its production. Yet leaders were also led. Still a small part of the economy, leading sectors were big enough to advance the general progress of invention across a broad front, enabling innovations to arise that would have been stunted a generation earlier.

CHAPTER TEN

Fruition

One attribute of an innovation system is the capacity to sustain innovation processes and begin new ones. By 1855 tens of thousands of U.S. practitioners could apply a wide variety of technological knowledge to many major innovations at the same time. The breadth of knowledge and the number of practitioners had advanced greatly from two decades earlier, expanding what and from whom one could learn. Practitioners now could simultaneously accelerate diffusion, deepen innovation in many fields, and generate innovations in new fields. And they did, further developing engines, sewing machines, harvesters, and cylinder presses; widening applications of mass production; and generating wholly new innovations in shoemaking and illuminants. Technological change had become ongoing and economy wide.

One indicator of the significance of innovative institutions was their capacity to spread and generate techniques when the economic environment offered less support. The growth of industrial production slowed from the mid-1850s; growth over the 1855–65 decade was around 30 percent as fast as the remarkable 120 percent of the previous decade.[1] The war itself was the greatest discontinuity, and the new political-economic setting must have affected innovation. Scarce capabilities might have stifled civilian innovation when wartime needs became more pressing. If innovation expanded in this unsettled context, the institutions in place when the tumultuous decade began had to play a role. Industry networks could have sustained progress where fundamental innovations had already occurred. Technological centers could have enabled basic innovations to form and develop in new or craft industries more quickly than earlier in the century. Deepening capabilities could have overcome barriers to inventive success, barriers that two decades earlier might have proven insurmountable. An innovation system might have consolidated.

A study of four innovations will help to understand the breadth of technological change in the turbulent decade. The Porter-Allen steam engine was a basic new technique in an established sector. Among innovations that broke new ground, few were more significant than shoe mechanization and the production and refining of petroleum. No diffusion process had greater importance than the radical expansion of wartime armament production. The four techniques indicate how innovation took on a dynamic of its own.

Diffusion and Ongoing Innovation

Important new inventions take time to develop and diffuse. The greatest productivity growth in any decade typically comes from the diffusion of past innovations. Present innovations have their impact in the future; the spread of recent innovations and incremental invention have greater immediate effect. Techniques practical by 1855 spread rapidly over the next decade. Stationary steam engines and railroad mileage doubled, McCormick sales tripled, all harvesting machines grew much faster, and sewing machine output grew 25 times. Thousands of minor changes contributed to the diffusion. Annual U.S. patents quadrupled to 3,770 in the 1856–65 decade. Much of the growth occurred where techniques already were practical. Woodworking, presses, textile, and telegraph patents roughly doubled from the previous decade; engine and railroad patents quadrupled, and patents for clocks, firearms, sewing machines, and harvesters grew even faster. Firms multiplied in most of these industries. Technical change was sustained as industrial production decelerated in part because products embodying recent innovations were improved by network learning and enjoyed rapid output growth.

Growth in established industries was punctuated by further innovations. Because networks and centers had matured, firms faced fewer problems in developing novel presses, reapers, sewing machines, and machine tools. This was certainly true for Joseph Brown, who drew on extensive contacts from manufacturers of tools, firearms, sewing machines, and machine tools to develop his universal milling machine. Especially in eastern cities, the breadth and depth of knowledge enabled more sophisticated innovations to succeed when they would not have earlier, much as Corliss had been able to draw on capabilities denied to Zachariah Allen.

The Porter high-speed engine is a case in point. The engine, workable by the time it was exhibited at the London Exhibition in 1862, operated at piston and rotating speeds from two to five times those of typical machines. The success-

ful engine combined Charles Porter's governor, John Allen's valve motion, and Charles Richards's steam engine indicator. The path of its success built on engine and steamboat networks, on machinery, engineering, and inventive centers—and on three stages of Porter's inventive career.[2]

A Hamilton College graduate, Charles Porter was a Rochester, New York, lawyer when first drawn to invention by a nonpaying client, who conned Porter to forgive his debt and invest in a scam invention. Undeterred, Porter bought a stone-dressing patent from another client, though this time first discussing it with the head of the Scientific American Patent Agency. Learning from publications and interactions with machinists, Porter made a prototype that failed, invented and built a machine, and formed a corporation to which he assigned his patent. Supportive contexts had deepened greatly over the past two decades. Porter studied production and design methods at three leading marine engine firms, contracted with machine shops to build precision parts, and studied texts to acquire design skills (table 10.1). He turned to high-speed operation after observing wood-planing and wood-molding machines. His plant adapted cranes from railroads. His machine worked well but was displaced by a basically superior stone-sawing technique.

From his stone-dressing experience Porter learned the advantages of high-speed designs and precision manufacture. The puzzle of small waves in the stone associated with changing engine speeds led him to his governor invention. After studying governors through publications and conversations with engineers and mathematicians, Porter built a governor with high rotating speeds and improved it at a machinist's suggestion. He purchased machine tools from two leading firms known for precision production, firms that also sold to Hoe and Colt. He designed a drilling machine with the help of Charles Richards, a former Colt worker who had become a New York machine designer; Francis Pratt built the machine. Porter emulated the precision manufacturing techniques of machine tool producers. He advertised effectively in the *Scientific American,* presenting "in every issue a fresh certificate of some disinterested person who has used his governor; thus forming an array of evidence which no man can help believing."[3]

Experience and contacts in selling and manufacturing the governor educated Porter in steam engineering and directed him to the high-speed engine. When trying to sell a governor, he met John Allen, who successfully operated a once-problematic engine for a New York hat firm. As a steamboat engineer, Allen had observed a defect in Corliss marine engines and developed valve motions to overcome the problem, with three engine patents to his credit. He relayed his ideas to Porter, who recognized that Allen's invention was well suited for a high-speed

Table 10.1. Sources of Learning for Charles Porter, 1850–1865

Invention	Activity	Source of Learning
Stone dresser	Purchased Hastings patent	Consulted with Munn, *Scientific American*
	Supervised machine building	Mott & Ayers
	Observed mechanics and drafting	Mott & Ayers
	Financed Porter invention	George Hope, Continental Fire Insurance Co.
	Learned drafting	Drafting Instruction book
	Observed machine design	Leading New York engine firms: Allaire, Morgan, Novelty
	High-speed design	Wood planing and molding machines
	Stone-dressing patent, 1854	Assigned to own company
	Cranes for plant	RR freight-handling uses
	Contracts for parts	Joseph Banks, machinist
Governor	Consultation about governors	Engineers and mathematicians
	Engine study	Haswell's *Engineers' Pocket Book*
	Governor improvement	John McLaren, machinist
	Governor patent, 1858	Assigned to own company
	Purchased machine tools	Aaron Freeland, George S. Lincoln, machinists
	Drawings for drilling machine	Charles Richards
	Manufacturing the drilling machine	Francis Pratt, at George Lincoln
	Observed and adopted twist drills	George Lincoln's plant
	Precision grinding techniques	Aaron Freeland
	Governor article and ads	*Scientific American*
	Exhibit at fair, silver medal	American Institute, 1859
	Learning from users	
Engine	Porter met John Allen	Engineer, New York hat manufacture
	Allen presented valve motion	Invented to solve problem in Corliss engine
	Design and analysis	Charles Richards, engineer and inventor
	Porter designed overhanging crank	Visited engine rooms
	Flywheel and pulley boring	Adaptation of Novelty Works hub boring
	Measurement of engine efficiency	McNaught indicator, made by Novelty
	High-speed engine indicator	Richards, at Porter's recommendation
	Indicator made and first used	Novelty Iron Works, 1861
	Indicator assigned partly to Porter	Patented at Novelty's suggestion
	London Exhibition, 1862	Parts by Freeland and British firms
	Presentation of Richard indicator	British Association for the Advancement of Science

Sources: Charles T. Porter, *Engineering Reminiscences Contributed to "Power" and "American Machinist"* (New York: John Wiley & Sons, 1908); see also nn. 2 and 3 for chap. 10.

steam engine, an object Allen had not imagined. The two men employed Charles Richards to analyze the system, and through their combined efforts the engine was perfected. Compared to engines with comparable power, the high-speed engine took up less space, required smaller flywheels and less gearing, and, most important, delivered smoother motion. Porter used his governor experience and his considerable contacts to meet the demanding precision requirements of the engine. He then encouraged Richards to design an instrument to measure the engine's efficiency, which Richards partly assigned to Porter and the Novelty Iron Works produced. Porter's presentation of the engine and indicator at the London Exhibition in 1862 marked its technical success. Counterintuitive design changes improved the engine for the Paris Exposition. Porter's later efforts to understand his engine's performance affected engineering theory, probably his greatest impact.[4] In Mokyr's terms prescriptive knowledge fed back into propositional knowledge.

The quick development of the Porter-Allen engine had several sources. From his stone-dressing machine through his governor, Porter learned from networks of practitioners, and the governor involved him in engine networks. He benefited from technological convergences. High-speed designs applied to woodworking machines, stone dressers, governors, and engines, and Allen's marine engine design was well suited to stationary uses. Precision methods for other uses applied to engine manufacture. Porter's interactions with engine makers, machine tool firms, and users of his governor supplied indispensable production knowledge. As engine speed increased, so did precision requirements, and Porter learned from leaders over the course of the 1850s. Publications and experts such as Richards, trained in precision machine design at Colt, provided systematic knowledge. Patent assignment enticed Porter into machine production and invention and enabled him to form two firms and control Richards's indicator. Networks and centers far in advance of those Corliss had faced 15 years earlier sped up his invention.[5]

Many significant innovations after 1855 did not benefit from the sophisticated urban environment in which Porter invented. Agricultural innovations in the West or resource extraction in rural areas could not call upon the same capabilities locally, though the movement of machinists, capital goods, and publications linked them to eastern developments. But in East and West alike, changes over the previous two decades increased knowledge, multiplied the knowledgeable, and enabled simultaneous improvements in locomotives, cylinder presses, circular saws, figure weaving, telegraphs, harvesters, machine tools, and many other sectors.

Mechanizing the Gentle Craft

As earlier innovation deepened in some industries, new innovation transformed others. Mechanization came to shoes and hats. Kelly and Bessemer interests began to mass-produce steel. Tunneling and rock-drilling machines modified construction and mining. Petroleum was the most notable new resource. New techniques manufactured paper from wood pulp. Better microscopes and photographic techniques joined other instrument improvements. New armaments destroyed more effectively, and artificial limbs mitigated some of the results. In each case innovators had to acquire knowledge of distinctive technological problems and their solutions. Spillovers from other sectors were essential to pose and solve such problems, as shoemaking and petroleum illustrate.

The shoe industry was among the largest in 1860, with 9 percent of manufacturing workers and almost 6 percent of value added. Shoemaking had evolved through the expansion of putting out and the birth of the pegged shoe. Mechanization overthrew the craft dynamic. The transformation rested on continuities with prior mechanization and patenting and on the discontinuity of war. Supported by New England textile, sewing, and woodworking networks, innovators challenged the two basic parts of the putting-out system, which made uppers and united uppers with soles. Initial mechanization applied the dry-thread sewing machine to light leather. John Nichols adapted one of the first Singer machines to shoe uppers and then designed shoe-sewing machines for Singer and for Grover and Baker. Major sewing machine firms dominated the market. A more fundamental change mechanized waxed-thread stitching on heavier uppers. William Wickersham solved the problem of sewing with waxed threads by using an awl, a hooked needle, and a looper to form a chain stitch. Like Nichols, Wickersham was part of the eastern Massachusetts machinery community, but he had considerably broader interests. Working as a machinist and philosophical instrument maker in Lowell, where Howe and other sewing machine inventors had labored, Wickersham was professionally linked to invention. In 1851 he advertised that he would "give his personal attention to the construction of Models for Patent Machinery of all kinds, and to the repairing of optical instruments."[6] Making patent models, it is unsurprising that he was attuned to local machinery improvements; he invented cloth-pressing irons and filtering devices at the same time that he mechanized shoe sewing. The Boston-area machinists William Butterfield and Edgar Stevens built and sold his machine. Threatened with patent litigation, Wickersham assigned rights to Elmer Townsend, who used this patent and those of three other inventors to make a machine that diffused widely in the

regional shoe industry.[7] With this machine mechanization came to much of upper production by 1860.

The transformation of shoe bottoming began with pegging. Pegging machines had been invented as early as 1829, but real progress waited until the mid-1850s. Townsend, the key entrepreneur, proceeded through patent purchase, beginning with John Greenough's 1854 invention. Greenough had worked as a machinist for the Patent Office, patented a sewing machine in 1842, invented woodworking equipment, became a patent agent, and published a respected mechanics' journal. He put this extraordinary background to work in designing his pegging machine, which had the shape and feed of a sewing machine and formed its own wood pegs. Townsend bought patents from five others, all machinists or professional inventors, but succeeded only when he purchased rights from Benjamin Sturtevant. A Maine shoemaker who became a Boston machinist, Sturtevant first assigned Townsend a lasting tool and later five more patents. He did not assign his most important invention, a design for a ribbon of peg wood cut from the circumference of a log and a lathe to make it; instead, he sold peg strips himself.[8]

Machine-using shoemakers, machinists searching for profitable products, and the patent system combined to lead to the first practical bottom-sewing machine. The central innovator, Lyman Blake, linked shoemaking, machinery, and patents systems. Blake was a Massachusetts shoemaker trained in machine-sewed uppers. He distributed Singer machines and trained others to use them before forming an upper-sewing shop. Pondering the problem of bottom sewing, he developed and patented a machine to stitch through the upper and soles using a rotating hook to feed thread on the inside of the shoe. His shoe design emulated the pegged shoe and departed from the hand-sewed shoe, which stitched the upper to an inner sole and welt in one seam and the welt to the outer sole in another. Recognizing that he lacked the capabilities to produce and sell the machine, Blake turned to patent assignment. Three competitors vied for the patent rights. The first failed to make payments, but the second, Gordon McKay, succeeded with a down payment of $8,000 and the promise to pay $62,000 more.[9]

McKay was one of a host of emergent machinist-entrepreneurs. Trained as a civil engineer, he worked on railroads and the Erie Canal. Around 1845 he set up a Pittsfield, Massachusetts, machine shop to repair textile and paper machines. Here he began patenting with a steam engine. In 1852 he became the general manager of the Lawrence Machine Shop, which built textile and a great variety of other machinery, including his engine. Lawrence used McKay's engine to run machinery at the New York Crystal Palace Exhibition in 1853. McKay invented two printing presses, which Lawrence manufactured. On the lookout for oppor-

tunities, he investigated shoemaking, witnessing one pegging machine patent. Through a Boston patent agent he learned of Blake's patent and efforts to buy it. Recognizing its potential, he entered the market and won the competition with Edgar Stevens and other New England machinists.[10]

McKay knew he needed to develop the invention, and he, Blake, and hired inventors set about to do so. The Civil War advanced the cause. McKay secured federal contracts for soldiers' footwear, and through 1862 he made 150,000 pairs. The revenue helped; McKay reported royalties of almost $100,000 in 1864. Wartime sales allowed McKay to improve the machine. In applying to renew his patent, Blake noted that army contracts were "undertaken with a view to test the machine, that it might be rendered as perfect as possible before it was sold to the public." Although the army rejected some of the shoes, revenues enabled McKay to develop the machine. McKay received six shoe-sewing patents and five related shoemaking patents from 1862 to 1865, six jointly with Blake. Blake received four other patents, and two employed inventors improved the machine.[11] Emulating sewing machine firms, McKay set up company sales agencies. To overcome problems of high fixed costs for small shoe manufacturers, he leased the machine rather than selling it. Along with military contracts he developed the machine to make women's shoes. Fostered by army sales of over 470,000 pairs, the machine was poised to penetrate the civilian market soon after the war.[12]

Shoemaking invention extended to lasting, other bottoming operations, soles and heels, upper cutting, and various tools and work-support devices. Fewer than 30 percent of shoe inventors with known occupations were machinists, below the share of any sector except clock making, telegraphs, and bridges (table 10.2).[13] In the latter two sectors applied scientists made up the gap, but few shoe inventors had scientific or inventive occupations. Machinists and applied scientists patented more but secured only 45 percent of internal patents, under the share of any sector except clock making and firearms, in which internal craftsmen had mechanical knowledge. Most other shoe inventors were from manufacturing occupations, almost four-fifths of whom made shoes, lasts, and shoe tools. Many learned in industry networks, including half the machinists.

Machinists and other technological occupations played several roles in shoe innovation. Machinists invented sophisticated machines. They constituted 56 percent of sewing and pegging machine inventors. Machinists' higher average patenting was due largely to their concentration on machine invention, in which many became principals or regular inventors.[14] Many utilized training in related industries. John Bradshaw was a textile machinist who received the first improvement patent on Howe's sewing machine before turning to pegging machines.

Table 10.2. Shoe Inventors by Occupation and Patent Type

	All	Machinists	Science and Invention	Other Manufacturing	Trade and Service	Network	Non-network
Inventors	81	23	5	41	12	48	33
Inventor share	100.0%	28.4%	6.2%	50.6%	14.8%	59.3%	40.7%
Shoe patents	1.88	2.39	2.60	1.68	1.25	2.13	1.52
Crossover patents	2.06	3.04	5.40	1.63	0.25	1.79	2.45
Pegging and sewing	25	14	3	7	1	16	9
Inventor share	100.0%	56.0%	12.0%	28.0%	4.0%	64.0%	36.0%
Shoe patents	3.40	3.21	3.67	3.86	2.00	3.88	2.56
Crossover patents	4.60	4.21	4.33	6.00	1.00	4.81	4.22
Other inventors	56	9	2	34	11	32	24
Inventor share	100.0%	16.1%	3.6%	60.7%	19.6%	57.1%	42.9%
Shoe patents	1.20	1.11	1.00	1.24	1.18	1.25	1.13
Crossover patents	0.93	1.22	7.00	0.74	0.18	0.28	1.79

Sources: Occupations were derived from city directories. Patents numbers were taken from the U.S. Patent Office classification for shoe manufacturing, and the patents were researched in the *Annual Reports of the Commissioner of Patents* through 1865.

At least seven inventors had been trained in sewing machine firms; four first patented sewing machines. Machinists made up only 16 percent of inventors for other operations; shoemakers and a few last makers and toolmakers were far more important in developing shoe designs, manufacturing processes, and tools. Machinists' design and production skills supported all invention. Being parts of eastern networks helped manufacture machines; McKay and a pegging machine firm bought Brown and Sharpe's universal milling machines by the mid-1860s.

Shoemaking networks centered around Massachusetts, where the shoe industry and shoe invention had long been concentrated. Mechanization modified knowledge in shoemakers' networks, so that craftsmen such as Blake learned mechanical techniques. Massachusetts inventors received 55 percent of shoemaking patents after 1855. The prospect for forming machinery firms and assigning patents encouraged shoemakers and machinists to invent. By the 1850s Massachusetts investors sought out profitable inventions, and patent assignment was common. Townsend is known to have bought 35 patents from 14 inventors, including 7 shoe-sewing machines and 20 other shoe machines. Half of the 39 inventors researched assigned at least one shoe patent to others, including nearly two-thirds of machinists, inventors, and applied scientists. McKay and others gained use without assigning their patents.

As an industry that was already mass-producing for national markets, shoemaking had clear potential demand for machinery. Networks and centers helped

realize the potential. Inventors from textile and apparel sectors utilized convergent technologies that spread readily in eastern New England. A spillover from firearms was essential; without the pattern lathe that had been applied to make standard shoe lasts, bottoming machinery could not make standard sizes.[15] Broader groups of machinists contributed to invention and machine production. Virtually all major improvements were patented, and some were assigned. Patent agents relayed information to potential entrants. Formed around machinery firms and factory users, networks sustained and extended mechanization. Machine usage, accelerated by military contracts for machine-made sewed and pegged shoes, already captured civilian markets by 1865. By then, the trajectory of factory shoemaking was well established.

New Resources

Compared to shoemaking, innovations in petroleum were much less continuous. Whereas shoemaking developed when nearby machinists with related technological knowledge transformed an established craft using its traditional material, the petroleum revolution involved each technological center and many industries in several areas of the country utilizing a new material. The great discovery—Edwin Drake's 1859 Titusville well—was a much-trumpeted qualitative break, but its significance, and perhaps its very existence, derived from the capabilities of pharmaceutical and chemical firms, leading academic chemists, salt producers, pump makers, lamp makers, and many others. Drake's accomplishment in an underdeveloped part of Pennsylvania depended from the start on eastern, urban capabilities.

To succeed, the petroleum industry required adequate reserves and potential demand but also techniques to pump, store, transport, distill, and use oil. By the 1850s petroleum had three potential markets. It was widely used for medical purposes, most commonly as a liniment. Heavier oils were used as lubricants. Illumination had the biggest potential; petroleum could be used to replace whale oil, lard oil, camphene, coal-based illuminating gas, and coal oil.[16] The illumination market was well established; in 1860 lamps, fixtures, and illuminants employed nearly 1 percent of the manufacturing labor force with twice as much value added, led by illuminating gas.

Petroleum production drew on several established techniques. Drilling techniques had developed in salt wells, especially in Kanasha County, West Virginia. From 1806 producers developed methods to drill through rock to depths of 1,500 feet and pump up brine. The original wooden tubing was replaced by tin and

then copper. By the 1830s steam engines drove the pumps; in 1838, 61 wells were run by small engines overwhelmingly made in Pittsburgh. The flatboat, steamboat, and railroad could move oil; the steam revolution thus played roles in extraction stationary and transportation uses. Tanks and barrels to store petroleum were common.[17] Domestic industries molded sheet brass, pressed glass, and adapted lamps of European design to use camphene and, from 1850, coal oil and petroleum. Pittsburgh and other cities in the trans-Allegheny West were centers of steam and metalworking capabilities.

In the most complex task distillation transformed crude oil into usable products. Although the chemistry of petroleum would not be understood until long after it came into use, other illuminants and lubricants provided a model. Isaiah Jennings, the versatile machinist-inventor of the Jennings rifle and steam engines, patented the first synthetic illuminant, camphene, and in 17 illumination and chemical patents from 1829 through 1850 developed methods to distill it from turpentine and lamps to burn it. From the 1830s illuminating gas was produced widely through a simple process that heated coal and purified the resulting gases; other localities used natural gas to the same end. Improved techniques and large-scale urban production spread gas illumination, including a million-dollar investment in Philadelphia.

Europeans pioneered the manufacture of coal oil, mostly for lubrication. The American coal oil industry, begun in the mid-1850s, provided central underpinnings to the petroleum industry. Coal oil was a by-product of efforts to produce illuminating gas and lubricants. Abraham Gesner received seven patents for coal oil, which he called "kerosene," and set up a New York firm to manufacture and distribute it. More important was a Boston firm, formed by pharmaceutical manufacturers and a sperm oil producer to make lubricating oil from coal tar, utilizing a process Luther Atwood patented in 1853. While introducing the technique in Scotland, Atwood and another company employee, Joshua Merrill, discovered a way to make an excellent illuminant from coal tar naphthas. Their firm turned to illuminants, and, using 13 more patents by Atwood, 7 by Merrill, and patent licenses from a British inventor, it learned to produce, distill, and purify coal oil. It also developed cracking techniques to increase yields of illuminants. American sulfuric acid manufacturers Supplied needed inputs. By 1858 kerosene was a commercial success, cheaper than sperm oil and safer than camphene. New York and Boston led, with Pittsburgh following. Some firms applied distilling techniques to petroleum, but the modest petroleum supply prevented it from competing with coal oil.[18]

The process that introduced petroleum as a fundamentally important resource began in 1851, when a Dartmouth-trained doctor, Francis Brewer, joined a lum-

ber firm in Titusville, Pennsylvania. Having used petroleum as a medicine, he was intrigued by local oil that was gathered off the surface of springs. Without science his efforts would have come to nothing. Brewer had a petroleum sample analyzed at Dartmouth, where a chemist encouraged him and put him in touch with a future partner. A campus visit by a Dartmouth alumnus began a process that led to the formation of the Pennsylvania Rock Oil Company in 1855 to buy land and develop petroleum. Luther Atwood and the eminent Yale chemistry professor, Benjamin Silliman Jr., submitted favorable reports. The Silliman Report, which has been called "perhaps the most epochal report in petroleum history," synthesized knowledge of petroleum, raised the possibility of changing its molecular structure at high heat, and—most important for the company—estimated that at least half of the crude could be transformed into illuminants. Producers learned from other industries. By 1861 major coal oil firms applied their techniques to refine petroleum. Drillers migrated from salt well regions. Steamboats along the Allegheny River and railroads transported oil. Coal oil lamps were adapted to burn petroleum. Multiplying wells throughout the region, including the first gushers, rapid growth of refining capacity, and falling prices marked the permanence of the industry. In 1860 petroleum output reached coal oil's 200,000 barrels; in 1862 petroleum's 3 million barrels dwarfed coal oil output.[19]

Initial petroleum production was quite backward. Titusville was located in a timber and farming area distant from railroads. The Pennsylvania Rock Oil Company hired E. L. Drake, a railroad conductor, to supervise its affairs. Who decided to drill for oil is unclear, but Drake hired a salt driller to bore a well. Drilling was slower than in salt wells; animals powered some efforts. Teamsters transported the oil, and new refiners were small and primitive.

From drilling to final use, petroleum production would change, and the change was well under way by 1865. Improved drilling methods included casing to prevent flooding and superior pump design. Portable steam engines powered drills and pumps; horsepower grew as wells deepened. Gas replaced wood and coal as a fuel. Power was transmitted more effectively to the drill. Torpedoing used gunpowder and then nitroglycerin to open wells clogged by paraffin. Watertight barrels and tanks improved storage. Floating methods, copied from lumber, moved oil to the Allegheny River. Pipelines, well known in urban water and gas systems, brought oil to rivers and railroads from 1865. By that date railroads, some with tank cars, moved into regional towns.[20]

Applied scientists improved refining methods. The advances, though proceeding with little recognition of concurrent discoveries in organic chemistry, employed chemical knowledge of specific gravities and boiling points of petro-

leum fractions and Silliman's observations on fractional distillation and cracking. Much of the knowledge came from coal oil refiners in which Merrill and Atwood quickly adapted their techniques to petroleum. Sugar refining also contributed. Petroleum refiners adopted existing terminology, measures, testing procedures, and distillation methods but required further changes. Instrument makers developed temperature- and ignition-testing devices for distilling. Refiners improved distillation and cracking techniques and developed methods for purifying distilled petroleum. The petroleum industry generated adequate products so quickly because it drew on techniques and personnel from other sectors.[21]

Few of the initial capabilities came from the oil area itself, although it did develop and even export skills in drilling, transportation, and storage. The wider region supplied critical capabilities. Pittsburgh had already developed coal oil production and became the regional center for the petroleum industry. Its 1861 city directory listed 11 oil merchants (both "coal and carbon"), 1 oil barrel factory, 3 oil tool manufacturers, and 4 oil pump and salt tube manufacturers. Refineries grew for coal oil and petroleum. Firms offered "pure white burning oil" and lubricants, some together with lamps. In 1863 the directory listed 40 dealers selling crude and refined oil, 22 refiners, 3 oil brokers, 1 barrel manufacturer, 1 barrel dealer, 3 oil tank manufacturers, and 1 shipper, who stored and forwarded oil. In addition, brass founders, coppersmiths, and sheet iron producers offered to equip and repair refineries, and engine and boiler firms offered power and refining equipment.[22]

Firms from other regions contributed. Most important were the New York and Boston refineries, which led in distilling improvements. The major coal oil firms all moved into petroleum. John and Giuseppe Tagliabue developed devices to measure specific gravity, product uniformity, and explosiveness. They had long been leading New York instrument makers; Giuseppe had made and invented thermometers, barometers, hydrometers, and other instruments used by the Coastal Survey and by firms making alcohol, sugar, food, and other products. The Utica-based Wood and Mann Steam Engine Company targeted its portable steam engine at well drillers, who would not need to erect fixed engine rooms. Its engine already had been used to run circular saws, wood planers, stonecutters, tanneries, churns, and threshers and was readily adapted to drill and pump. So important was the petroleum market that the firm set up an agency in Titusville and sold not only engines but also "oil well outfits complete." Its catalog included nine Titusville references and an equal number from other petroleum areas.[23]

Patents demonstrate how petroleum methods benefited from wider knowledge. Over 100 patentees improved petroleum production (mostly wells and stor-

age) and refining (including coal oil improvements that applied to petroleum). They received about 200 petroleum patents and another 40 for related coal gas or oil lamp operations (table 10.3). Well over half of the inventors had scientific or inventive occupations. Almost a third of them were chemists, who distilled petroleum and coal oil or made soap, pharmaceuticals, and glue. A fifth were engineers and patent agents. Inventors from scientific and inventive operations received four-fifths of refining patents and half of drilling and other production patents. Machinists, less common than in most innovations, concentrated on the mechanical sides of the industry, especially drilling and related operations. Other manufacturers had a modest share of patents but were important for testing devices. Only a quarter of inventors had jobs in petroleum networks, but they received three-fifths of refining patents. Applied scientists, supplemented by machinists and instrument makers, were essential to petroleum usage and invention.

Inventors learned from earlier patenting. Over half of those with multiple patents invented in related fields before making their petroleum inventions. Half of them patented gas and oil techniques. Several had chemical patents, and a half-dozen invented pumps and steam-measuring devices. Others invented rock drills, water wells, and thermometers.

Invention was national in scope. Petroleum production localized in a few counties of northwestern Pennsylvania, but only seven inventors located in that area, concentrating almost entirely on drilling. Inventors in cities with populations over 10,000 received almost three-quarters of petroleum patents. They were especially important in refining, holding four-fifths of patents, but urban inventors also received two-thirds of drilling and related extraction patents. Rural western Pennsylvania developed petroleum production so fast because other industries and regions supplied critical knowledge.

Unlike shoemaking, which involved learning from a few well-defined, nearby sectors, petroleum entailed learning from many disparate, dispersed industries. Among major innovators only a few mechanized shoemaking, all with background in textiles, sewing machines, or shoemaking. Many more contributed to petroleum and lighting development, and their backgrounds were diverse. Academic and industrial chemists played a particularly large role, from Silliman's studies of petroleum through chemists improving refining and using explosives in drilling. The United States was a follower in academic and industrial chemistry, but it followed closely enough to be able to provide inputs such as sulfuric acid and knowledge needed to innovate in coal- and petroleum-based chemicals. Organic chemistry was in its infancy, and innovations largely concerned mechanical design and the physical control of production.[24] Coal-based gas and oil industries

Table 10.3. Petroleum Patentees by Occupation

	All	Machinists	Science and Invention	Other Manufacturing	Trade and Service	Agriculture	Network
Inventors	107	8	30	4	10	1	13
Inventor share (%)	100.0	15.1	56.6	7.5	18.9	1.9	24.5
Petroleum patents	2.22	2.50	3.70	2.00	1.60	1.00	4.69
Other patents	2.69	5.50	4.07	2.75	6.00	7.00	2.31
Share, refining patents (%)	100.0	4.1	81.1	5.4	9.5	0	59.5
Share, well patents (%)	100.0	33.3	51.0	2.0	11.8	2.0	17.6
Multiple patents (%)	67.3	100.0	96.7	50.0	70.0	100.0	92.3
With earlier patents (%)	51.4	100.0	80.0	50.0	60.0	100.0	84.6
With earlier related patents (%)	27.1	25.0	46.7	50.0	30.0	0	69.2

Sources: U.S. Patent Office, *Subject Matter Index of Patents for Inventions Issued by the United States Patent Office from 1790 to 1873, Inclusive* (Washington, D.C.: Government Printing Office, 1874); *Annual Reports of the Commissioner of Patents,* 1847–65.

Note: Occupations could be determined for 53 patentees. Petroleum patents here include petroleum, coal oil and coal gas patents. Well patents include drilling and a few for storage and transportation. Related patents include those for water wells, steam pumps and gauges, chemical transformations, and drilling.

were leaders. Drilling techniques spilled over from saltmaking. A long line of pump improvers set the stage for petroleum pumping and piping; the Worthington pump would become an industry standard. Engines and transportation were found at hand. Eastern brass workers developed lamps that burned whale oil, camphene, coal oil, and then petroleum. Machinists designed and made refining machinery and occasionally opened refineries. Patents and scientific assessments supplied conditions for forming corporations, and wide licensing of some core patents, especially those of the British inventor James Young, eased entry into refining. Paul David and Gavin Wright have argued that American resource abundance rested on having the resources and being able to utilize them.[25] In the case of petroleum many prior technological changes and each technological center enabled rapid resource usage.

Industrializing War

The Civil War marked a great discontinuity in economic life. The North was cut off from the South and the South from foreign trade. With two million northern-

ers in the military, labor supply was disrupted. At the same time, governments required huge increases in munitions and other supplies; the U.S. Army increased its material purchases from under $10 million in 1860 to $628 million in 1865. Some goods were little altered, such as apparel and wagons, and resources could be redeployed within industries. But to raise ordnance purchases from $1.5 to $43 million required a huge increase in capacity, much of it in new products.[26] Moreover, the government regained coordination functions that had declined with the contract system in the 1830s. The North's ability to multiply and improve its wartime production affected the war's outcome. It also manifested the adaptability of technological capabilities that had materialized over the previous decades.

Wartime needs put northern experience in mechanization to wide use, resulting in perhaps the first industrial war. Whereas the Crimean War was fought with largely handmade arms and provisions, Union soldiers wore machine-sewed uniforms and McKay and machine-pegged shoes, traveled by railroad, communicated by telegraph, and fought with mass-produced firearms, innovative ammunition, and new artillery. Ironclad steamships took sailors to sea, including Monitors with turret-rotated heavy armaments made in major shipyards in the East and smaller yards in the West. The industrial war built on prior industrialization.

The scale and quickness of redeployment rested on the capabilities of industries and centers. Major innovators demonstrated the depth of redeployment. Eighty-five major innovators produced or invented military firearms, ordnance, warships, machinery to make them, or new products for government contracts, all but two in the North (table 10.4). They constituted a quarter of all major innovators alive during the war, and many others invented or produced goods used in the war. Over half of war-related innovators continued lines of production and invention begun before the war, including engineers and manufacturers of firearms, steam engines, ships, locomotives, machine tools, shoemaking machines, hardware, condensed milk, and artificial legs. Established dynamics thus contributed directly to the war effort. But 46 percent of war-related innovators invented or made military equipment for the first time. Generic machinists and others specializing in textiles, machine tools, and printing presses made firearms or firearms machinery. Other metalworkers formed ordnance and armor. Civil engineers moved into naval engineering and military invention. The general knowledge such innovators possessed enabled the North to raise production with extraordinary rapidity. Machinists, engineers, and applied scientists were especially important; they made up four-fifths of military innovators, and related firearms and metalworking occupations made up half of the rest. The

Table 10.4. Civil War Contributions by Major Innovators

Background	Number	Production	Invention
Machinery			
Generic	8	firearms (2); cannon	rifling; firearms (3), machinery, revolving turrets
Machine tools	5	firearms machinery (4)	firearms
Steam engines	10	boat engines (7), Monitor, ship engineer; machinery	firearms (2); Monitor
Steamships	2	steamships (2); gun carriage	firearms; steamship
Locomotives	1	military locomotives	
Printing presses	2	firearms machinery (2)	
Textile machinery	4	firearms (3); machinery	firearms (3)
Sewing machines	1	gunpowder (Confederate)	
Shoemaking	2	military footwear	
Woodworking	2	rolled plates, bayonets	bayonets; firearms
Other metalworking			
Foundry	5	cannon balls; horseshoes; cannon; iron plate (2)	rifled cannon
Hardware	1	cannon	projectiles
Firearms	9	firearms (8)	firearms (5)
Brassmaking and lamps	2		firearms; warships
Wire drawing	1	ordnance	ordnance
Crafts			
Condensed milk	1	condensed milk	
Artificial limbs	1	artificial limbs	artificial limbs
Shipbuilding	1	Lifeboats	watertight wagon boat

Confederacy had few such benefits; one of its military innovators was trained at the U.S. Military Academy at West Point and the other invented sewing machines, which, ironically, were manufactured by Brown and Sharpe, whose machine tools equipped Union armories.

Munitions involved the greatest discontinuities of production and invention. The army required vastly greater quantities of small arms, heavy artillery, and ammunition. The navy needed ships for naval warfare and blockades. The case of small arms helps clarify how production could grow so precipitously. Army demands far exceeded what existing suppliers could meet. The federal army had destroyed the Harpers Ferry Armory, and Springfield could not approach the military demand. Faced with an immediate need, the Ordnance Department imported large quantities early in the war, including five-sixths of small arms purchased in the first year of the war and nearly all of the muskets and rifles. By 1862 domestic producers were the principal suppliers. The Springfield Armory was one source; it increased output from 14,000 firearms in 1861 to a high of 276,000

Background	Number	Production	Invention
Science and invention			
Civil engineer	8	maps; military railroad (2), naval engineer	firearms (2); projectiles; boats; torpedoes
Army engineer	3	Ordnance Department (3; 1 Confederate)	firearms; gunpowder
Naval engineer	2	Ordnance Department; naval engineer	cannon; warships
Chemist	4		ordnance; ship armor; gunpowder
Rubber	1	canteens; rubber pontoons	
Telegraph	1	military telegraph	
Draftsman	1	naval engineer	
Services			
Ship captain	2	ships	ships; balloon ship
River clearing	1	gunboat	gunboat
Lawyer	1	waterproof cartridge	waterproof cartridge
Other			
Real estate	1	machine gun	machine gun
Aeronaut	1	observation balloon	
Farmer	1		rifle

Sources: Dictionary of American Biography (New York: Scribner, 1937); *National Cyclopaedia of American Biography* (New York: J. T. White, 1898–); *A Biographical Dictionary of American Civil Engineers,* 2 vols. (New York: American Society of Civil Engineers, 1972 and 1991).

Note: Innovators alive during the war, numbering 321, were selected from an extended list of 444 innovators surveyed for patents; some had no patents.

in 1864, making about half of all Springfield rifles. Private domestic producers supplied close to 700,000 Springfield rifles and muskets, 400,000 breechloaders for cavalry and other use, and 360,000 revolvers. Altogether, private domestic firms doubled the Armory's output over the course of the war.[27]

The government sought interchangeable firearms made to its own patterns. Accomplishing this task was far from easy, even when the government loosened its standards. For even the most advanced firearms firm, making new weapons presented challenges. Colt manufactured 75,000 Springfield muskets, but initial retooling was so great that it contracted out the work. Firms without experience making interchangeable-parts firearms had to learn, and Colt's efforts to introduce the methods in Britain demonstrated the difficulties of the transition. Some private firms succeeded quickly; by 1863 eight had government purchases exceeding $500,000, some with no previous firearms experience.[28]

Three groups were responsible for the remarkable growth: the Ordnance Department and the Springfield Armory, the network of private firearms firms and skilled workers, and the broader community of machinists. Collectively, the groups updated the government-centered armory system in a more advanced

mechanical setting. The Ordnance Department let hundreds of firearms contracts over the course of the war. The Springfield Armory produced firearms, made spare parts for imported arms, and administered many private contracts. It issued pattern arms to contractors and worked with contractors to meet its standards, allowing them to use its equipment to make gauges. The Ordnance Department also inspected arms and certified that contracts had been met. The Armory purchased machine tools widely. Government engineers learned from firms; Ordnance Department and Springfield Armory personnel, for example, visited the Sellers plant in 1861. In the 1830s the Armory had become a "pivotal clearinghouse for the acquisition and dissemination of technical know-how"; it regained this position during the war as suppliers, and contractors regularly turned to it for help.[29]

Without an active network of private firms with interchangeable-parts experience, the government's ambitious goal would have been virtually impossible to realize. The network involved firearms firms, mostly in New England, together with skilled workers, inventors, and suppliers. The most advanced firm was the largest contractor; Colt had government sales of $4.7 million over the course of the war, concentrated in the period when other firms were coming online. Its Hartford competitor, Sharps Rifle, had been established for a decade, utilizing Robbins and Lawrence workers to organize its production process. It was the second largest domestic contractor at the beginning of the war and the third largest overall. Another established producer, Remington, was the second largest domestic contractor over the course of the war. Other firms well ensconced in the firearms network began production immediately before or during the war. The Colt employee Christopher Spencer formed a firm to make his repeating rifle, which had sales over $2 million in the second half of the war. Lamson, Goodnow and Yale produced in the old Robbins and Lawrence factory, led by another Robbins and Lawrence machinist. Two other leading contractors had been firearms inventors in the 1850s. Many smaller contractors had similar origins, including the Whitney Armory and several other New England firms.[30] The dynamics of the private firearms industry was a principal source of contractors with capabilities to mass-produce.

The broader machinery sector provided other sources of continuity. The supply of machine tools was a major barrier to rapid production growth. The Springfield Armory, Colt, and some established firms had the capability to make their own machine tools, but even they relied on purchased machinery. The Armory bought machine tools from 35 firms. Except for Colt, the American Watch Company, and a few others, they were all machinery firms. George

Lincoln, Pratt and Whitney, and some others were closely linked to the firearms industry, but most made machine tools, textile machinery, locomotives, engines, presses, woodworking machinery, and much more. The firms included leaders in precision production, including William Sellers, Bement and Dougherty, R. Hoe, Brown and Sharpe, and the Lowell Machine Shop.[31] Generic design and production skills that had been built up over the previous decade eased the entry into firearms machinery. Firms entered quickly; in August 1861 the *Scientific American* reported that the production of firearms machinery was "calling into requisition the resources of all our first-class machine shops," including "nearly the entire works of Messrs. Bement and Dougherty."[32] Coordination problems slowed expansion, as new contractors acquired specifications and patterns and dealt with annoyances such as mismatched screw threads. In early 1862 Hoe wrote to the Springfield Armory that "it is a matter of the greatest importance to us, that we have the patterns at once. We have lost much time already."[33] Learning grew with machine tool sales; Sellers had visitors from firms making firearms and firearm machinery throughout the war. Firms even publicized their advances; in 1862 Brown and Sharpe advertised a machine "for turning and cutting the thread on the breech pin of the Springfield Rifled Musket."[34]

Machinery firms also contracted to make firearms. A wide variety of firms made parts, including Stanley Rule and Level and the American Screw Company, often specializing in parts related to their core functions. Many firms made whole firearms. The Ordnance Department's list included Amoskeag and Mason (principally in textile machinery and locomotives), Parker, Snow and Company (hardware, engines, presses, pumps, and machine tools), and James Millholland (railroad equipment). The largest two, each totaling over $500,000 in contracts, were Alfred Jenks and Son and the Providence Tool Company. Jenks was one of the oldest textile machinery firms in the country, and its Philadelphia location provided proximity to Bement and Sellers. It studied Springfield Armory techniques in designing its plant.[35] Providence Tool specialized in hardware and specialized machinery such as cold-iron presses. From its initial forays into firearms, which it undertook "in a state of complete ignorance concerning the character of the work and the requirements of the Government," in two years it developed an advanced armory that made virtually every part of the rifle.[36] To its own metalworking expertise it added the capabilities of others. Its superintendent, Frederick Howe, perhaps the most original of the Robbins and Lawrence machinists, enjoyed the highest level of capabilities and extensive contacts. Partly through Howe's efforts, Providence Tool formed close working relations with Brown and Sharpe. It used Brown and Sharpe tapping machines to prepare the barrel for

insertion of the breech pin, the turret screw machine for a great variety of parts, and the universal milling machine, which Howe described as "exceedingly useful for making machine tools of every description."[37]

Private armories increased output so rapidly because they held universal mechanical knowledge, often had interchangeable-parts experience, and acquired knowledge through the Ordnance Department, the Springfield Armory, the mobility of workers, and relations to suppliers and subcontractors. Relations were not always cordial. Firms often failed to meet contracts and resented others' efforts to recruit workers they trained. The government argued with even leading contractors, such as R. Hoe, about the cost or quality of its products. But private deliveries of about 1.5 million arms greatly aided the war effort.

Established capabilities and network contacts benefited other military equipment. The biggest suppliers of heavy ordnance were three venerable foundries with long connections to the military—Cyrus Alger in Boston, active since the War of 1812, Robert Parrott's West Point Foundry, which made cannons since 1817, and Charles Knap's Pittsburgh foundry, which cast government cannon since 1814. Each had a history of experimental ordnance work, and Parrott, a West Point graduate, had been a captain of ordnance. The navy also depended on such continuities. Although Monitor-class vessels were basically new, the navy had been investing in steam warships for 15 years, and it continued to employ the same set of federal navy yards and private marine engine builders and shipyards that had built and equipped ships before the war. There were changes, such as new western Monitor builders, and some entrants did not succeed, including Corliss in building marine engines. But eastern and western firms used substantial engine and shipbuilding capabilities to multiply the number and modify the design of navy ships.[38]

Invention also took a warlike turn. Charles Porter noted, "The Civil War had just broken out, and every Yankee was making some warlike invention."[39] Firearms inventions increased significantly; surveyed patents grew by 77 percent from 1856–60 to 1861–65, when total patents grew by 22 percent. By one estimate the share of war-related patents tripled, though still amounting to only a tenth of all patents.[40] The discontinuity in pace was accompanied by one of personnel; only one-fifth of inventors first patenting firearms during the war years came from firearms networks, well below the one-third share over the whole period. If patenting could grow rapidly outside networks, how central were networks to technical change? Perhaps anyone could invent in response to surging demand.

Growing firearms patenting can reasonably be interpreted as a response to shifting potential markets. Yet though new inventors would have impacts later,

including some army and Ordnance Department officers, the basic wartime changes were well grounded in existing networks. Patenting growth continued a prewar trend that had increased firearms patents from 1856 through 1860 by 170 percent over the previous five years. Prewar network inventors were more likely to continue inventing during the war. They constituted 48 percent of all firearms inventors in the 1855–60 period, but 57 percent of those who continued inventing in the following five years. Persistent network inventors averaged almost three patents from 1861 through 1865, twice the average of inventors beginning during the war.[41] Almost half of the persistent inventors gained use, or at least the prospects of use, as principals in or assignees to firearms firms. Moreover, some who were beginning to invent during the war gained use with firms operating before the war, much as successful firms in other industries used the patents of new inventors.[42]

Antebellum inventors undertook the most significant advances in firearms. Breechloaders, repeaters, and metal ammunition were exceptional at the beginning of the war but had become weapons of choice at the war's end. The Ordnance Department had tested breechloaders in the 1850s but initially opposed their usage in the war, and Springfield produced none. Private producers educated in firearms networks in the 1850s were the key innovators, including Burnside, Sharps, and Spencer. Army officers, especially those linked to the cavalry, purchased breechloaders, and the Ordnance Department finally endorsed them. The war probably accelerated the adoption of breechloaders for military purposes, but they were already ascending in civilian uses.[43]

Firearms had led in interchangeable-parts mass production metalworking for a half-century before the war and continued to lead during the war. The Springfield Armory remained at the center of the learning, now supplemented by Colt and other private armories. Firearms firms, especially long-established ones, improved machining and forging techniques. Inventors from several firms patented lathes and planers to manufacture firearms, and unpatented improvements greatly extended their contribution. Capital goods firms ascended, including Pratt and Whitney, which built on its Colt training to sell mass production machinery extensively. Brown and Sharpe was particularly important; its lathes, tapping machines, and especially its universal miller were significant innovations in metalworking, with widespread ramifications. The needs of the Providence Tool Company's armory, together with Brown and Sharpe's own sewing machine production, occasioned the changes. The war probably sped up diffusion. By 1867 universal miller purchasers included five leading private firearms firms, the Springfield Armory, a government arsenal, a government navy yard, an am-

munition company, and three other machinery firms with wartime armories. The firm's screw machines had armaments markets that were just as wide.[44]

Antebellum firearms, ordnance, and shipbuilding networks—integrating the government, private firms, and inventors—underpinned the great weaponry expansion of the Civil War. The machinery sector provided invaluable inputs, personnel, and manufacturers. Mechanical engineers advanced heavy ordnance and warships. Applied science contributed chemical companies making gunpowder, civil engineers laying out military railroads, and military telegraphs. Technological centers were vital to northern advantages. New firms and wartime innovators contributed, much as they did in other technologies. But they, too, learned from leading industries and centers. In its magnitude and length the Civil War marked a great discontinuity, but capabilities established over the previous quarter-century enabled the North to increase and modify war output rapidly, while the South could not. Without the contrasting capabilities the war would have lasted longer and conceivably its outcome would have changed.

Simultaneity and Integration

Technological capabilities in many industries and technological centers enabled innovations to develop more quickly after 1855. The Porter-Allen engine, shoe mechanization, petroleum production, and mushrooming armament output each relied on previous innovations but varied in the relevant networks (engines or textiles or coal oil or firearms) and centers (machinery for each, chemicals for petroleum and firearms, patenting differently for each). The breadth of innovation was grounded in the variety and depth of previous developments.

The same factors help explain the simultaneity of innovation. During the war the northern economy multiplied military production, reduced the civilian labor force by a million workers, and still penetrated markets of earlier innovations and dedicated resources to new, largely civilian innovations. Steam engineering capabilities were dense enough that some could develop the Allen engine while others spread the Corliss engine and designed new steamships. Mass production firearms multiplied at the same time as interchangeable-parts sewing machines and watches appeared. Chemical resources developed petroleum refining and also explosives and pharmaceuticals. The United States had established a scale of capabilities sufficient to allow innovation on many fronts. Invention in some sectors did decline; clock and woodworking patents in the 1861–65 period did not reach half of the totals of the previous five years, and several other technologies fell modestly. But patenting in other sectors rose, including firearms, machine

tools, shoe machines, and petroleum as well as, less expectedly, textiles and engines. Widespread invention in part reflected the modest resource demands of even so destructive a war, when army shoe purchases were about 7 percent of northern production and war-related patents were only one-tenth of the total.[45] More fundamentally, it manifested a density of innovational capabilities sufficient to allow considerable redeployment without thwarting new initiatives and progress developing older ones.

Wartime innovation also resulted from greater interlinkages of innovations after 1855 than had occurred a generation earlier. Steam engineering broadened military and civilian uses. Convergent technologies connected textile and apparel sectors. Sewing machine production built on firearms production but contributed parts to firearms manufacturers. Machine tools developed for one use found many others. Design capabilities in one industry illuminated others. The momentum began to spur sectors in which the country lagged, including iron rolling and Bessemer steel. The economy could generate so many innovations because it had extensive technological capabilities arrayed so that innovation in some sectors informed innovation in others. An innovation system born in more peaceful times had come to fruition when the peace had been shattered.

CHAPTER ELEVEN

The First Innovation System

Perhaps the distinguishing characteristic of modern technological development—and indeed modern economic life—is that it builds on itself. Markets may tend toward equilibrium, but internally generated innovations always will disrupt such tendencies. In antebellum America knowledge-spreading institutions, technological innovations, and the economic effects of innovation formed a cumulative process bringing ongoing change to much of the economy—or, rather, many processes, including those within industries, inside the machinery sector, within general-purpose technologies, between convergent technologies, and into the broader scientific and technological communities. Collectively, the institutions that structured the generation and diffusion of technical change within and across industries made up the first innovation system in the United States.

Any innovation was a discontinuity, a break with existing practice that developed new techniques and products. Forming an innovation system involved a more radical break with the past. The railroad, telegraph, and harvester were novelties of great import, but they developed through machinery, applied science, and inventive occupations and organizations. The innovation system was structured around such technological centers, so its own origin had much less to rely on. Understanding how an innovation system emerged forms a fundamental problem.

The structure, spatial organization, and trajectory of the system governed its effects. The most basic issue concerned structure: how did an economy-spanning, innovation-promoting system operate and originate? The gap between the craft and farm economy at independence and the widely mechanized Civil War economy was so great that some account of the transition must be advanced. In considering the origins of the market economy, Adam Smith argued that a "previous" accumulation was necessary for the division of labor and ongoing

accumulation to occur.[1] Analogously, I have argued that previous innovation, occurring without the support of technological centers, helped form an innovation system. Hence, understanding ongoing technological change has involved accounts of innovation before centers formed, the formation of centers, and the more integrated innovation centers allowed. Knowledge and innovation were spatially structured, and innovation formed new networks that reshaped the spatial distribution of knowledge. Institutions spreading knowledge across industries further shaped the geography of knowledge. The scope of knowledge diffusion—local, regional, national, or international—shaped who learned, invented, and benefited. Finally, innovation developed a distinctive trajectory and a momentum that would sustain it. Antebellum knowledge-spreading networks and centers directed ongoing change well beyond the Civil War. Examining such attributes of the emergent innovation system will draw together the threads that make up this book.

Structures of Change

Franklin, Hamilton, Jefferson, and other advocates of the application of science to the useful arts expected innovation-supporting knowledge to come from Britain and other advanced countries, from scientific advances and government action, and from indigenous innovators, sources we have called innovation from abroad, from above, and from below. Interpretations of U.S. technological development differ fundamentally in the importance they ascribe to these sources. A focus on imported techniques views U.S. development as the spread of a European Industrial Revolution. Advocates of innovation from above emphasize the role of the scientific revolution and government policy in overcoming the chasm separating craft production from industrial innovation. The unique American environment might have spawned innovations from below in an otherwise backward country. I have argued that each source played a role in beginning and maintaining industrialization. The sources differed among industries, built on each other, and changed over time, as table 11.1 summarizes.

American industrialization rested on European developments but became more autonomous over time. Much of the U.S. Industrial Revolution began by transferring British textile, printing, and steam engine techniques. European transfers continued when self-acting mules, water turbines, locomotives, and planers arrived in the 1830s and 1840s. Diffusion rarely transformed production by itself; U.S. industries adapted and developed imported techniques, and in some cases, such as Evans's high-pressure engine, domestic invention led U.S.

Table 11.1. Sources of U.S. Innovation

	From Abroad	From Above: Science	From Above: Policy	From Below: Internal	From Below: Links
Textiles	Water frame; mules; loom	Water turbine	Patent system (for all techniques)	Lowell; ring spinning; carding	Metalworking; engines
Engines and navigation	Watt engine; knowledge of experiments	Steam engineering; mechanicians	Boiler regulation; river and coastal improvements	High-pressure steam engine; steamboat	Metalworking; instruments
Firearms	French model; personnel	Ordnance testing; mechanicians	Government coordination; ordnance development	Interchangeable parts	Metalworking
Printing	Cylinder presses			New presses	Metalworking
Clocks				Wood and brass clocks	Measurement; brass
Woodworking				Planers, lathes, mortising	Firearms; machinery
Locomotives	Locomotives	European techniques		4-2-0 and 4-4-0 engines	Metalworking; engines
Civil engineering	Canals, roads, railroads	College (Military Academy)	Topographical engineers	Railroad layout; bridges	Canals; bridges; roads
Telegraph	Electrical science	Scientific advances; college training	College training; government contract	Telegraph design and equipment	Machinery; construction methods
Harvesting				Harvesters and binders	Metalworking
Sewing machines				Sewing machines; mass production	Textiles; machine tools; firearms
Machine tools	Lathe; planer		Firearms contracting and co-ordination	Lathes; planers, turret lathes, milling machines	Firearms; textiles; presses; engines; instruments
Shoe machinery			Civil War contracts	Upper and bottom sewing; pegging	Sewing; metalworking; firearms
Petroleum	Coal oil and gas	Chemistry	Urban gas lighting	Illuminants and lubricants	Coal oil; gas; salt; lamps

techniques away from European methods. Many sectors relied little on knowledge flows from abroad. Even when international flows were important, they rested on domestic absorptive capacity and the activity of American firms. At times U.S. firms innovated in Europe before bringing the techniques home, such as the illuminating fluid that the Americans Luther Atwood and Joshua Merrill discovered when working in Britain. Innovation from abroad became relatively less important over time not because diffusion decreased but because internal innovation grew. With stronger domestic capabilities, learning from abroad was better organized and often quicker later in the period, as U.S. firms scoured European techniques and Europeans saw the United States as potential markets they could more easily penetrate when they could patent in the United States and find domestic partners. Diffusion occurred more regularly when it was less essential.

Learning from above involved knowledge that was generated or transmitted outside the economy so that economic development rested on scientific advance or policy decisions. Frontier science was decisive in telegraphs but relatively unimportant in other sectors. Engineering knowledge was more widely significant; without it water turbines, well-constructed rail lines and bridges, and petroleum distillation and filtration systems would not have been possible nearly as quickly. Propositional knowledge—classified as science by contemporaries—had yet broader effects. Mechanicians trained in colleges, mechanics' institutes, and other civil organizations constituted almost half of major innovators over the period. Their share grew over time, suggesting that the application of science was far more than a way to compensate for original underdevelopment. Civil organizations structured research and set standards. The Franklin Institute undertook careful, influential analysis of waterwheel design, steam engine explosions, and a wide array of inventions. Under the leadership of William Sellers, it studied screw thread configurations and in 1864 proposed what was to become the U.S. standard, helping to overcome coordination problems facing many sectors. Institutes helped shape a technical community that transmitted knowledge across occupations.[2] College faculty explored for resources, reported on analyses of chemicals and minerals (such as Silliman's report on petroleum), and consulted with firms and government committees. Innovation from above helped overcome early U.S. backwardness in engines and firearms, but it was more generally important later in the period.

The federal government played a vital role in developing interchangeable-parts firearms, and its topographical engineers sped railroad development. Government's wider effects were less direct. The patent system provided incentives to invent and formed a key underpinning to technological communication after

the mid-1820s, when the *Journal of the Franklin Institute,* reports of the commissioner of patents, and the *Scientific American* came to spread knowledge widely. It structured much invention; though some important innovations were not patented, most were. Infrastructural improvements by federal, state, and local governments integrated markets and developed skills. The government played wider roles in education and knowledge transmission. The expansion of primary and high school education, especially in the North and West, improved capabilities to absorb technological knowledge; 45 percent of major innovators attended high school. College education was only exceptionally public, but the Military Academy came to provide rigorous scientific and engineering training. Free speech rights, subsidized postal rates, and high literacy rates supported the press. The general and technical press reported inventions, highlighted valuable patents being contested in court, and advertised job openings or patent sale. After his 1853 visit to the United States, Joseph Whitworth emphasized the combination of widespread public education in the North and an uncontrolled press: "Among the many benefits which arise from their joint co-operation may be ranked most prominently the value which they teach men to place upon intelligent contrivance; the readiness with which they cause new improvements to be received, and the impulse which they thus unavoidably give to [the] inventive spirit."[3]

Even when scientists, educators, and publishers developed and spread knowledge, innovators overwhelmingly came from manufacturing occupations, engineering, patent agencies, and, for agricultural improvements, farming. The bulk of major innovators, a larger share of inventors, and an even greater share of commercializers gained useful knowledge within the U.S. economy. How such innovation from below developed new techniques varied over the period.

Innovators were more social products than the individualistic entrepreneurs Schumpeter envisioned. In most techniques many invented before practicality was achieved, reflecting a common recognition of potential demand and the capability to invent. Pioneers who gained assistance developing and producing the new technique succeeded much more commonly than those innovating by themselves. This is not to deny the significance of personal character and insight; the persistence of a McCormick or a Morse brought innovations to fruition sooner than they otherwise would have. But success relied on access to knowledge transmitted by labor mobility, capital goods sale, and invention, and had one innovator not made use of the knowledge, others might have. Early pioneers faced hurdles to inventing, producing, and marketing that handicrafts could not surmount. Science and learning from abroad solved some of the problems, but many relied on knowledge developed within the innovation path. Partly for this

reason, early industrialization involved many failures and slow successes. In textiles, presses, engines, and clocks, problems were overcome by finding simpler techniques that were easier to make practical, even if they were inferior to known techniques that were harder to realize.

Early in the development of any innovation, inventors and users formed networks that communicated technological knowledge and addressed problems. Participants typically included users of techniques and capital goods producers but extended to applied scientists in telegraphs, civil engineering, petroleum, and armaments. Networks delineated paths of cumulative technological development. Along these paths some inventions gained commercial success, diffused through worker mobility and capital goods sale, widened learning about the new techniques, and prompted continued invention. Emulators linked to pioneers copied techniques. Networks sped diffusion by building on already high mobility among firms. New networks built around innovation transformed older occupations, as the textile machinery network did the hand weavers' craft. The prolonged period spent developing an invention to practicality—often a dozen or more years—slowed its initial diffusion, but diffusion accelerated as knowledge spread. Secondary innovations started their own diffusion cycles, as ring spinning, Corliss engines, cylinder presses, brass clocks, 4-4-0 engines, grain binders, and sole-sewing machines replaced earlier techniques. Networks themselves evolved when machinery spread as capital goods, speeding diffusion and adding to network membership. For the economy as a whole, innovation consisted of a number of paths, each resting on distinct knowledge transmitted in different networks.

Case studies have demonstrated the importance of networks for invention. In thirteen technology types with significant patenting in the antebellum period, about 1,660 inventors from 1836 through 1865 with known occupations received over 6,900 patents. Those with network linkages constituted over two-fifths of all inventors, and, using network knowledge, their 2.8 internal patents far exceeded the 1.9 for nonnetwork inventors (table 11.2). As a result, they received over half of all internal patents. Network inventors from technological occupations were especially proficient. Making up one-fifth of all inventors, their 3.5 internal patents generated 31 percent of such patents. Those outside networks patented most readily if they held technological occupations that supplied applicable knowledge. Nontechnological occupations outside networks were least well positioned to learn and received fewer than one-fifth of internal patents.

Innovation paths were not self-contained. The United States had particularly extensive occupational mobility, and some inventors used knowledge from earlier occupations in later ones.[4] Inventors learned of opportunities outside their

Table 11.2. Inventors and Patents, Thirteen Technology Types, 1836–1865

	All	Technological Network Occupations	Other Network Occupations	Technological Nonnetwork Occupations	Other Nonnetwork Occupations
Share of inventors	—	20.0%	22.1%	33.4%	24.5%
Average internal patents	2.27	3.50	2.18	2.03	1.69
Internal patent share	—	30.7%	21.2%	29.9%	18.2%
Average number of crossover patents	1.89	1.95	0.81	2.63	1.80
Crossover patent share	—	20.6%	9.5%	46.5%	23.3%

Sources: For data and methodology, see Ross Thomson, "Networks, Communal Knowledge, and the Location of Invention in Antebellum America," presented in the Economic History Association meetings, Austin Tex., 2007.

Note: The technology types are the 12 reported in table 9.5 and shoe manufacturing. If petroleum had been included, the significance of technological occupations would have increased. Patents include all issued to inventors. Internal patents are those within studied technology type (including those initially surveyed and others in that type); the average of 2.3 internal patents exceeds the 1.7 initially surveyed patents. All others are crossover patents. Totals have been adjusted for double counting when inventors appeared in more than one technology type.

occupations from consumption, communities, civil organizations, and publications. After 1830 existing innovative paths became interlinked, and new innovations rested on the accomplishments of earlier ones (table 11.1). Machinists originating in early-industrializing sectors often spread machine tools, forging methods, and casting techniques to other industries. Machinists also utilized design capabilities acquired in some sectors to develop others; the links were particularly direct in the cases of locomotives, sewing machines, and shoe machines. Engineers used canal methods to build railroads. Although the telegraph had little grounding in economically significant applied science, petroleum rested on coal oil and chemical methods.

As paths integrated, cumulative economic processes altered. Network dynamics were complemented and at times underpinned by techniques transmitted from other industries. New machine tools made more sophisticated, durable printing presses, steam engines, textile machines, locomotives, and sewing machines, bolstering growth in early-industrializing sectors and in new industries. As demand for machine tools grew, they were further improved. The integration of paths extended to other production convergences and to design convergences; as the cases of textiles and firearms indicate, the mobility of workers supported development in a wide range of sectors.

The growth of cross-industry spillovers marked a qualitative change in U.S. innovation. Developments before the 1830s were substantially independent of

each other. This was true of the industries examined in detail and others considered in passing, such as salt, nails, and brass. Industries benefited from common institutions, such as the patent system and schools. But such institutions did relatively little to communicate technological knowledge among industries, because published patent claims dated from the 1820s, and schools outside the Military Academy focused on generic capabilities and pure science. The Industrial Revolution sectors, canals, and emerging technical publications and mechanics' institutes laid the basis for linking development across networks. They were principal sources of technological centers of machinists, engineers and applied scientists, and patent agents and inventive personnel who spread knowledge across industries. These centers became essential parts of the innovation system that was emerging in the 1830s.

The expanding cross-industry linkages shed light on the discontinuity of the birth of an innovation system. For the whole economy innovation developed in two stages. A first stage developed techniques in many separate and largely unconnected processes. The developments were slowed by the inadequate production and design capabilities of the craft and farm economy. But they did improve production and design skills and in so doing formed a body of machinists and applied scientists central to a stage of linked development. In the second stage worker mobility, commodity sale, and firm diversification extended innovation in existing sectors and expanded it to others. Technological occupations led in crossover invention; they received two-thirds of crossover patents in major technologies (table 11.2). Widening innovation, in turn, augmented technological centers, fueling further invention. The Industrial Revolution through 1830 was thus important in itself and also for the ongoing change it helped generate.

Cross-industry invention rested on spillovers within the economy. It also depended, at times decisively, on knowledge generated abroad or from above. Scientific knowledge became more vital over time. American practitioners made more systematic use of European advances as they studied patents and toured Europe and as Europeans traveled or patented in the United States. Many scientists consulted regularly. Inventors also contributed to scientific advance. Inadequate knowledge of engine efficiency or petroleum refining helped propel research in thermodynamics and organic chemistry. Advances in instrumentation benefited scientific research. Feedbacks with applied science were greater yet. Innovators often led mechanics' associations, including Matthias Baldwin and William Sellers at the Franklin Institute. The curricula at West Point and Rensselaer Polytechnic Institute were affected by civilian needs. Industrialists occasionally funded college chairs, including Harvard's Rumsford professorship. Innovators

also published widely; one-sixth of major innovators published on technological and scientific subjects by 1865. Needless to say, U.S. economic development hardly determined scientific advance or civil organization in the United States. But it helped shape bodies of propositional knowledge and modes of dissemination that supported technological change in ways far beyond those in 1790 or 1835.

By the Civil War well-defined technological centers, structured around a machinery sector, applied science organizations and occupations, and a patent system, readily spread technological knowledge. Centers linked innovation paths; they strengthened and multiplied the institutions propelling distinct industry dynamics. Centers were relatively small; in 1860 they employed about 90,000 people, including all machinists, engineers, chemists, and patent agents, and another 55,000 if physicians are added. Technological occupations had grown greatly; machinists had quadrupled in the previous twenty years, and other groups expanded at similar rates. Centers were increasingly interdependent. Machinists participated in applied science organizations and read publications, while engineers complemented machinists in infrastructural projects. Patent agents and examiners were inventors and applied scientists. The centers each linked to broader groups of machine users, scientists, and assignees, who in turn were connected through patent usage, civil institutions, and consultation. The result was a loosely integrated techno-inventive community oriented to, and successful at, the practical use of knowledge. Because the community was spatially structured, so was the innovation system.

Geography

Innovation systems are often portrayed as being national in scope, with differences based on nation-specific characteristics. Although they are aware that innovative institutions could be local, regional, international, or even global, many argue for the nation as the most significant, or at least a vitally important, unit.[5] This study illuminates the issue in a period when an innovation system came into being.

Innovation concentrated where knowledge and the capability to use it were available. Technological knowledge, the ability to use it, and innovation were unevenly distributed across the United States. Learning located where networks and centers congregated. Cities and manufacturing regions had the edge. Boston, New York, and Philadelphia were notable, with their large machinery sectors, important engineering and chemical firms, patent agents, leading colleges, and strong mechanics' institutes. Concentrations of technological occupations also

arose in Baltimore, Buffalo, Cincinnati, Hartford, New Haven, Newark, Pittsburg, Providence, Wilmington, and Worcester. Secondary cities were particularly important in the United States; whereas British invention concentrated in London, U.S. invention was more widely dispersed. Among randomly selected patentees, urban inventors were six times as frequent as nonurban inventors on a per capita basis, and they averaged 50 percent more patents. Cities communicated to their hinterlands, and hinterland inventors also invented widely.

Regions formed a clear hierarchy reflecting the distribution of networks, centers, and cities. New England and Mid-Atlantic regions dominated 1836–65 patenting among inventors with known occupations in 13 major technologies. New England had 3.7 times as many patents per capita as the nation's average, Mid-Atlantic states 90 percent above the average, while on the other extreme the South had only 8 percent of the nation's average (table 11.3). The regional patenting gap reflected, most significantly, differences in inventors per capita (the inventor per capita index) and, secondarily, patents per inventor. The South, for example, had 11 percent of the nation's average number of inventors per capita, and their 2.9 average patents made up seven-tenths of the national average.[6]

The great variation of regional patent shares correlated with differences in the shares of network occupations. Regions where networks had not extended had little invention. For the 13 technology types network density is expressed in the network per capita index, which compares regional shares of network occupations per capita. The Mid-Atlantic States and especially New England had much greater concentrations of network members, which helps explain their higher patents per capita. The West had fewer network occupations and fewer inventors, and the South lagged greatly in both. As learning within networks increased, so did invention.

Some regions, however, had many more inventors relative to network members. New England had 75 percent more inventors than network members compared to the national average (the inventor per network index), the Middle States 54 percent more, but the South had only 28 percent as many inventors as network workers, a share that was only modestly higher had Civil War patenting been omitted. Interestingly, regions differed in the inventor-network ratio across technologies; the gap reflected characteristics of regions more than of technologies.[7]

The gap between inventors and network shares can be explained in part because most innovations occurred in the East, and knowledge spread most readily in that area, where labor mobility was common and capital goods production was centered. Two other factors were at work. Regions with high shares of inventors relative to networks also had relatively high shares of technological occupa-

Table 11.3. Regional Inventive Unevenness, Thirteen Technology Types, 1836–1865

	New England	Mid-Atlantic	South	West
Share of all patents	36.2%	48.7%	2.5%	12.6%
Patent per capita index	3.67	1.86	0.08	0.41
Inventor per capita index	3.76	1.64	0.11	0.53
Average internal patents	2.27	2.38	1.85	2.06
Average crossover patents	1.78	2.33	1.10	1.14
Network per capita index	2.16	1.07	0.38	0.58
Inventor per network index	1.75	1.54	0.28	0.92
Technological concentration index	2.18	1.53	0.40	0.83
Urbanization index	1.63	2.14	0.32	0.56

Sources: See table 11.2.

Note: All data are adjusted for double counting. Indexes identify a region compared to the nation as a whole; an index of 2 means that the region was twice the national average. The patent per capita index is a region's patents per capita compared to the national average (or, identically, its share of patents relative to its share of 1860 population). The inventor per capita index is a region's share of inventors relative to its share of population and analogously for the network per capita index. Networks were measured by shares of relevant occupations in 1860. The inventor per network index is the region's share of inventors relative to its share of networks. The technological concentration index is a region's share of technological occupations in 1860 relative to its population share. The urbanization index is the region's share of population in cities over 10,000 relative to the national average. Data from 1860 were used because the average patent of the period was issued during the 1860 census year.

tions. Such occupations concentrated in the East; as the technological concentration index notes, New England had 2.2 times the national average of such workers in 1860 and the South but 40 percent. Technological occupations centered exactly where inventors were most common relative to networks.

Moreover, the most urban regions also had the highest shares of inventors relative to networks. The Mid-Atlantic States had twice the urban concentration of the nation and New England 60 percent more, whereas the West had 56 percent of the national average and the South 32 percent (see the urbanization index). Cities were centers of inventive capital goods firms; 58 percent of machinery industry employees worked in urban counties. Cities also supported inventors through their concentration of machinists, model builders, and patent agents. The concentration of technological occupations and cities in the East led to greater crossover patenting; their inventors averaged 2.1 crossovers, compared to 1.1 for the West and South. Indeed, the single most prolific group combined these attributes: inventors from technological occupations in major cities—those who were most integrated into technological centers—averaged 3.1 crossover patents. The eastern concentration of networks, technological occupations, and cities provided more learning that led to a concentration of invention and patenting.[8]

Particular kinds of knowledge concentrated spatially, and regions, accordingly, specialized by innovation. New England led in textiles, clocks, and shoemaking. The Middle States led in steam engines, railroads, telegraphs, and petroleum. The two regions shared the lead in presses, firearms, and sewing machines. Reaper invention concentrated in the West and western New York.[9] In this sense innovation systems in particular industries were regional, though they were rarely confined to one region.

In cases such as textiles cumulative development led to greater regional specialization of manufacturing, learning, and invention. In other cases diffusion spread knowledge over time, and invention located over wider areas. Yet invention did not broaden evenly. The West expanded its share of all patents from 4.5 percent before 1836 to 17.3 percent from 1836 through 1860, while the South's share fell from 9.5 to 7.8 percent. Several factors contributed to the contrast. By 1850 the West had twice as much manufacturing and machinery employment per capita. Although both regions had major cities, the Midwest had many more small cities and towns and more modestly sized manufacturing firms.[10] Midwestern education levels were higher, and diffusion from the East to the Midwest was much higher than from the East to the South, including machinists and inventors. Inventors born in New England frequently patented in the Middle States, and vice versa, and over one-third of western inventors migrated from New England and the Mid-Atlantic (see table 4.8). But eastern migrants rarely invented in the South.

National institutions did structure technological change in a way that united much of the country, though less effectively integrating the South. Government policy often underpinned national systems, and the patent system, tariffs, river and coastal improvements, firearms development, and the Military Academy conferred national advantages. The steamboat and railroad helped integrate the national economy, though the railroad's most significant linkages were east-west. Ever since Evans expanded from his Philadelphia plant to another one in Pittsburgh, mobility was common across the Alleghenies. Engine production extended down the Ohio River to Cincinnati and Louisville. The West and East had similar educational and infrastructural policies and a similar proclivity to form mechanics' institutes and other civil organizations. Manufacturing spread westward. Technologically, the West was an externalization of the East in a way that the South was not. As engineers, patent agents, and machinists spread across western cities, inventors and users became integrated in one innovation system.

The innovation system was also integrated into European developments. Even as American technology became more autonomous, links with European tech-

niques deepened. Foreign inventors were allowed to patent in the United States in 1836, though at substantially higher cost. Many did, including Richard Roberts, James Nasmyth, and Henry Bessemer; foreign citizens received about 2 percent of U.S. patents after 1836, led by the British. U.S. inventors patented more extensively in Britain. Americans studied at European colleges in chemistry and other fields. Immigration brought European techniques, as it had throughout the century. Among randomly sampled inventors one-sixth were foreign born, and they invented in every part of the country.[11]

Although they were linked to Europe, U.S. innovative institutions were largely independent and often different. Firms that learned from abroad configured techniques to fit American conditions and developed them in ways that did not quickly transfer back. Networks and centers were largely domestic, though enriched with imports. Some U.S. machinists and inventors migrated to Europe, but their numbers were dwarfed by Europeans coming to the United States. Markets for engineers, machinists, and the crafts were substantially internal to the country (though often including eastern Canada). Abundant resources and relatively expensive labor led to different choices of technique. Innovation took different directions, leading to the notable success of American reapers, lock making, and interchangeable-parts firearms at London's Crystal Palace. And as Samuel Colt and Alfred Hobbs discovered when they tried to use American methods in Britain, transfer was no mean feat. Innovation systems did not lose their national dimension by learning from other nations. Indeed, systems differed in how well they learned from others.[12] Extraeconomic factors reinforced the national character of innovation. Superior public education formed distinct capabilities. The U.S. patent examination system increased the enforceability of the patent, and patenting costs were under one-tenth of those in Britain. These factors increased patenting per capita to levels twice as high as in Britain from 1810 through 1880, except for the 1840–57 period, when over half of U.S. applications were rejected, but even then U.S. applications doubled British patents on a per capita basis.[13] The United States was developing its own technologies, its own knowledge-transmitting institutions, and its own technological trajectories.

Trajectories

The technological momentum characteristic of innovation systems is hard to start and, once established, difficult to stop. Major innovations have to overcome a series of complementary obstacles, each of which limits diffusion. More recent innovations in electrical power and computers took a half-century to have major

effects, limited by demand and incentive problems, the need for complementary innovations, and constrained knowledge diffusion.[14] Antebellum innovations faced similar limits and one more: the fundamental barrier that basic design and production capabilities were only coming into being, which slowed the generation and spread of techniques. British and American machine tool innovations spread fitfully. Already a half-century old, the engine lathe was unused in many areas in the 1850s. The steam engine, practical for stationary uses by 1812 in the United States and 30 years earlier in Britain, powered only half of the U.S. manufacturing sector in 1870. Although still constrained by weak capabilities, networks had generated momentum in developing and diffusing techniques in several industries by the 1830s. Growing technological occupations deepened and widened innovation over time; momentum in some industries helped initiate momentum in others. Annual patents grew sevenfold from the late 1830s to the late 1850s, and assignments grew at least as fast.[15] The techno-economic momentum deepened over the period and continued through and beyond the Civil War.[16]

U.S. innovation was particularly wide ranging. In contrast to Schumpeter's view that a few innovations drove economic development, many innovations, widespread invention, and cross-industry spillovers all propelled technological change. Virtually from the beginning, innovation in the United States was broader than in England. Along with textiles, engines, presses, canals, and similar Industrial Revolution techniques, by 1835 the nation innovated in woodworking, firearms, clocks, and steamboats. Later on, the United States transferred railroads and initiated telegraphs, reapers, sewing machines, shoe machines, and petroleum refining.[17] American economic conditions shaped the choices, resulting in relatively more steamboats, fewer stationary engines, more reapers, and faster but more wasteful woodworking machines. But the choices themselves evolved as networks and centers improved techniques in a context of expanding, relatively homogeneous markets. If America benefited from what Max Weber called "democratic demand"—and it likely did—so, too, did it benefit from democratic invention.[18]

The multiplicity of U.S. innovations broadened learning, extended spillovers, and formed common problems. Technological leaders utilized knowledge from some industries to solve problems in others. Textiles advanced sewing, waterpower, and the transmission of motion. Engines supported power-driven mechanization and steam-driven locomotives, pumps, dredges, tunneling devices, and warships. Woodworking revolutionized construction, furniture, wagons, and shoe lasts. Firearms and clocks generated interchangeable-parts techniques that applied in many sectors. Machine tools applied everywhere. From the 1830s tech-

nological centers led the proliferation of mechanical developments, construction innovations, chemical improvements, and attempts to apply electricity to the telegraph, locomotives, lights, and medical cures. Extraeconomic changes in mechanics' institutes, colleges, and the patent system added impetus. New rounds of innovations had their own spillovers.

The social division of labor reflected the change. In 1860 about half of the workers in machinery firms with known specializations made sewing, harvesting, electrical, locomotive, and other machines created since 1830. Machinists, engineers, chemists, draftsmen, and patent agents ascended, while hand loom weavers, gunsmiths, and hand stitchers declined. Some contributors to early industrialization also succumbed, including millwrights. As George Gibb puts it: "Here was a typical example of the course of industrial progress. The great breast wheels, the individualistic work of the master millwright, slowly yielded place to the higher efficiency and lower cost of the turbine—manufactured in standard sizes for standard installations. The millwright himself—a craftsman existing by tolerance in an age which had grown away from handcraftsmanship—was to disappear with his wheels, his place in the industrial system being taken by the hydraulic engineer."[19]

Innovation formed a trajectory that crossed much of the economy. Technological change mechanized production "with a rapidity that is altogether unprecedented," as Joseph Whitworth put it.[20] Machines embodied knowledge in their movements. In the textile factory, Zachariah Allen wrote in his 1829 *Science of Mechanics,* "Mere machines are made to operate with apparently as much self directed skill as is exhibited in the manual labour of intelligent beings." The power loom, Whittemore's carding equipment, and mill gearing require "only the inspection of a workman or superintendent." In such machines "mere matter is made to appear to possess the attributes of mind."[21] Whitworth noted the mechanization of innumerable crafts; firearms and woodworking machines were among the most distinctive. The "universal application of machinery" distinguished American development.[22]

Mass production developed widely. Interchangeable-parts production was the most complete form. Full interchangeability was exceptional; even in firearms manufacturing, labor-saving approximations were more common. Yet the principle of interchangeability and equipment to realize it organized production in firearms and incipiently in other sectors. Mass production applied much more widely outside interchangeable parts, including efforts to make standard sizes of textiles or shoes or doors or locomotive parts in order to reach mass markets or facilitate repair. Standards and means to realize them were required for any

kind of mass production, and Joseph Brown's wire measures in the early 1850s and William Sellers's standard American screw thread a decade later helped secure such production. In some industries mass production gave advantages to capital-intensive, large-scale plants, though mechanized farms, garment shops, and woodworking factories had modest scale economies.

Precision had long been sought to create better vacuums in engines or reduce friction and increase machine speed and durability. But it was not easy to achieve. Whitworth noted that American lathes were less accurate than British counterparts, and Joseph Brown confirmed their inaccuracy when he had to rebuild them to make sewing machines. Having accurate planing machines and engine lathes was a necessary starting point. By the 1850s Hoe found U.S. machine tools to be more precise than those he purchased from Whitworth. Measurement devices, too, were needed. Brown and Sharpe made rulers and vernier and micrometer calipers for shop use. The Tagliabues moved from thermometers to apparatus to aid chemical analysis and petroleum distillation. Steam-measuring methods improved, including Charles Richards's steam engine indicator, which Charles Porter thought "made high-speed engineering possible."[23]

Innovation also targeted resource extraction and utilization. Whitworth attributed woodworking mechanization in part to the abundance of wood in the United States; circular saws, fast lathes, planers, and mortising machines all sped the processing and utilization of this resource. Machines to drill rock, tunnel, and saw stone spread in mines, quarries, and construction. The massive movement into petroleum extraction and refining demonstrated that capabilities existed to extend resource usage quickly and effectively.

The trajectory's components reinforced each other. Precision improvements supported mechanization and mass production by enabling machines to work faster and more accurately. Mechanization sped resource extraction and processing, and cheaper resources encouraged mechanization. Demand linkages extended the feedbacks. Expanding mechanization augmented machine tool sales. The railroad integrated markets, fostered mass production, and encouraged diffusion of Bessemer steel methods. The steam engine and the railroad enabled production to concentrate in cities and industrial regions, where learning and invention were greater.

Each aspect of the trajectory was shared with other countries, but the United States formed a distinctive mix of greater mechanization, mass production for more homogeneous markets, and extensive resource utilization. In textiles, engines, presses, machine tools, locomotives, and the telegraph, the United States shared techniques with Europe, but U.S. methods differed, with reliance on high-

pressure steam, ring spinning, and Morse telegraphs. In other sectors the United States originated techniques and used them more extensively, such as mass-produced clocks, watches, and firearms; mass production machine tools and forging methods; and machines to work wood, sew, harvest, and refine petroleum. The United States received three-quarters of its awards at the 1867 Paris Exposition in such utilitarian industries and won others for scales, locks, washing machines, and plows.[24] Such technologies distinguished the content of the U.S. innovation system.

The technological trajectory continued during the war and in the years that followed. Wartime innovation built on the established technological dynamic and added to it. Firms moving into military products during the war commonly returned to civilian products afterward. Still, wartime experience brought interchangeable-parts metalworking to more firms, and some retained the practices. Wartime interchangeable-parts diffusion should not be overestimated; most firms using Brown and Sharpe milling and screw-making techniques located in industries expected to use such machines. Yet firms that grew rapidly through wartime orders led later mass production machine tool development, especially Brown and Sharpe and Pratt and Whitney, and firearms methods spread to other sectors.[25] Those trained in firearms techniques would use them into the automobile age. Henry Leland was an apprentice machinist in the Crompton Loom Works when that firm got a contract to make gun-stocking lathes for the Springfield Armory. Leland made tools to make these lathes and then worked at the Armory during the war and at the Colt armory in 1865. Stays in rifle and machine tool firms led him seven years later to Brown and Sharpe,, where he made screw machines, sewing machines, and grinding machines. He put this knowledge to use in his Detroit machine shop, where he made bicycle parts, internal combustion engines, machine tools, and castings for Ransom Olds's automobile, built the first Cadillac car, and ultimately headed that company.[26]

The 1865 economy was vastly different than when Samuel Slater emigrated 75 years earlier. The Providence area illustrates the change. In the quarter-century after 1790 Slater and David Wilkinson made the area a center of textiles and textile machinery. In the next quarter-century Providence developed more complex textile machinery and became a regional center of screw making and engine making, though Zachariah Allen's cutoff patent failed and Joseph Brown could not find enough business to specialize in machine tools. The area fundamentally changed in the third quarter-century. After 1840 James Brown, who had once been Wilkinson's apprentice, became a leading producer of self-acting mules and operated an armory during the war; Thomas Hill, Slater's former partner, made

textiles machines. Providence was a center of sophisticated stationary engines, led by Corliss and including Babcock and Wilcox. Frederick Howe's Providence Tool Company was a leading hardware and firearms firm, the American Screw Company dominated gimlet-pointed screw making, and the Gorham Manufacturing Company applied drop forges to silverware. The Hope Iron Works made drop presses, machine tools, engines, and windlasses. Joseph Brown advanced precision measurement, interchangeable-parts sewing machines, and machine tools, with a dozen area customers for his milling and screw machines. Other firms made textiles, files, pumps, locomotives, machine tools, nails, jewelry, and gas. Brown University educated leading chemists and mechanical engineers.[27] With different emphases many parts of the northern economy changed as fundamentally. The Mechanical Age was far more advanced in 1865 than when Thomas Carlyle so named it 36 years earlier.

Much of the trajectory was in its infancy. Machinery had penetrated textiles, printing, and much of woodworking, but it was still spreading in steam power and harvesting, only beginning in shoemaking and grain binding, and unused in many craft operations. Files and chisels pervaded machine shops. Already established in clocks and firearms, mass production was just starting in watches and sewing machines. Precise equipment was hard to come by, and standards in screw threads and other devices were only beginning to form. Abundant resources were used extensively, but systematic resource discovery, transportation, and processing were just dawning in petroleum and minerals.

Yet the trajectory of innovation was deeply embedded in occupations and organizations. Short of a fundamental calamity—such as a southern conquest of the North, which the very trajectory made unlikely—momentum along the technological path would continue. Machinists would continue to move among industries, invent, and form new firms. Having doubled from 1840 to 1850 and quintupled over the next decade, patents nearly tripled from 1860 through 1870 and doubled through the mid-1880s. After 1845 inventors patented more continuously. One-fifth of surveyed patentees from 1847 through 1865 also patented after the war, and their postwar patents exceeded their earlier efforts. Ascending inventors were nurtured by the same institutions that had trained a generation of inventors from the 1830s. One was Thomas Edison, who, as a 17-year-old itinerant telegrapher in 1864, read the *Telegrapher,* studied science books, and invented a telegraph recorder. His first patent would come four years later.[28]

The antebellum path of technological progress structured innovation after the war. The path was not, of course, unchanging. Already large firms institutionalized invention, at times anticipating R&D labs that would appear later in the cen-

tury. Western Union, Singer, Wheeler and Wilson, McCormick, Hoe, and several railroads incorporated features of managerial firms, and the firms of Gordon McKay and the Cleveland oil refiner John D. Rockefeller would acquire the same properties. The trend among major innovators toward college and scientific education also continued after the war.[29] Advances in thermodynamics, electromagnetism, and organic chemistry would alter science-based innovation. Wartime policy changes, including the Morrill Act, would greatly expand collegiate applied science education and research over the following decades. Such changes would differentiate postbellum innovation.

Yet earlier dynamics remained and, indeed, strengthened. Machinists, applied scientists, and inventive occupations continued to shape innovation. William Sellers followed his 21 patents received through 1865 with 68 afterward. Adding to his fundamental machine tool inventions, Joseph Brown patented the universal grinding machine in 1876. Moses Farmer received 24 patents through 1865 and three times as many afterward. Even as some firms grew large, new firm formation, often grounded in or leading to invention, continued unabated. Patent agents and machinery workers doubled from 1860 to 1870, both a result and a cause of growing invention. The road had been paved, or at least surveyed, to wider mechanization and mass production, precision capital goods, systematic resource extraction, large-scale engineering projects, and, led by Edison, electrification.

Although Edison's lab foreshadowed another system of innovation, the antebellum mode expanded its impact as the century progressed. The first innovation system, growing in sophistication and extent, could not but propel the United States along and beyond its antebellum trajectory. Learning had acquired an institutional structure that would bring the United States to world economic leadership.

Selected Primary Sources and Data Sets

The contentions of this book rest on evidence from dozens of data sets and firm records, many used in several chapters. The specific kinds of evidence were discussed when first used, but an overview of the evidence and key assumptions might prove a useful reference. The appendix examines principal primary data sets on patents, inventions, patent assignments, output, and other activities as well as listing firm records consulted. For each it identifies the chapters in which the sources were used.

Patents

The book uses over 60 distinct sets of patent and invention data. Table A.1 lists these sets, their selection method, the chapters in which they were used, and the number of relevant patents, patentees, or individuals surveyed. One group, called the technology samples, is drawn from a survey of patents. A few of them are based upon U.S. Patent Office official classifications, including sewing machines, shoe machines, and telegraphs. The official classifications begin in 1836, when patents were first numbered, and in these three cases, all relevant patents were issued from 1836 forward. Most technology data sets selected patents based on keywords (such as *spinning, weaving, looms,* and *carding* for textiles, or *locomotives, railroads, railroad cars, switches,* and *brakes* for railroads), using an 1873 listing of all U.S. patent grants. This method omits many patents that are picked up in the classifications and so cannot claim to be complete. But it does allow the formation of a consistent set of patents from 1790 to 1865, not simply from 1836 on, and so can examine the growth of patents over time. It also catches many relevant patents not listed in the narrow classifications. A comparison of the keyword selection procedure with the use of patent classifications suggests that the procedure introduces no biases. (The sources for all data sets were listed the first time the sets were used in each chapter.)

Other data sets are drawn from a survey of individuals, not patents. These sets determine all patents, usually from 1790 through 1865, for each inventor. The individuals are selected from (a) the technology samples, (b) a random sample of all inventors from 1790 through 1865, selected from lists of patentees (called the all-inventor sample), (c) a study of major innovators listed in biographical dictionaries, (d) a study

of selected groups including principals of machinery firms, engineers, patents agents, patent examiners, and Franklin Institute leaders.

The sources used posed particular problems for achieving a random sample of inventors in the all-inventor sample. The sources were alphabetical lists of patentees in each year from 1847 through 1865 and in a compilation of all patents from 1790 through 1846. A random sample of patents could not be used because it would bias the selection toward those with more than one patent in any year. My procedure was to pick randomly distributed locations in the reports (such as page 79, 8 centimeters from the top) and to pick the inventor after the one in that position. To have picked the one in that position would have biased the selection toward patentees with more patents (and hence taking up more space) in any report. The number of patentees chosen in each year was proportional to the number of patents, except that I oversampled in the years 1790–1846 to get enough patentees for meaningful comparisons over time.

Although this procedure randomly selected inventors within any year, it did not overcome the problem that those patenting in more than one year had more chances of being selected. In a random sample each patentee from 1790 through 1865 would have an equal chance of being selected. My sampling procedure does so within each year, but because inventors could have been selected from 20 different sources—the cumulative index of patents through 1846 and annual reports from 1847 through 1865—patentees listed in more than one of these sources had more chances to be selected. I compensate by weighing the patents of inventors by the reciprocal of the number of years in which they invented. An inventor who patented in 10 different years (including the 1790–1846 index as one "year"), for example, had 10 times the likelihood of being selected as an inventor in only one year. By the procedure adopted, this inventor would be weighed at 0.1 if sampled in one year, 0.2 if sampled in two years, and so forth. An alternative procedure would be to restrict the data set—say to those sampled in their first year of patenting—but doing so would lose considerable data. A smaller bias, the oversampling of inventors from 1790 through 1846, can be corrected by reducing their importance in proportion to the numbers of patents in these years compared to later years. Because machinists invented in more years, their adjusted share fell relative to their unadjusted share.

All patents from 1790 through 1865 were ascertained for each patentee. In determining whether inventors with similar names were in fact the same person, I adopted three conventions. First, I assumed that two patentees with the same name and location were indeed the same person. Second, I assumed that two patentees with the same name in different locations but with the same types of patents were the same person but were not the same person if the patent types were different. Because inventors were highly mobile, this procedure understates the total number of patents issued to an inventor. Third, I assumed that two patentees with the same name and location but with no patents less than 15 years apart were not the same person (an assumption to rule out counting fathers and sons as the same person).

Occupations were determined from city directories and from 1850 and 1860 population censuses. Because occupational change was frequent, I included occupations

only if they were documented three years or fewer from the patent grant. If occupations at the time of the sampled patent could not be determined, I searched for the times of other patents. This procedure and the availability of city directories only for urban inventors biased the occupations toward more urban and more prolific inventors.

Finally, the New York Exhibition samples identify U.S. exhibitors at the 1853 New York Crystal Palace Exhibition, including selected categories to match technology samples, and all exhibitors outside of fine arts and minerals. In the former group about three-fifths of the exhibits were patented.

Patent Assignments

The Patent Office began recording patent assignments in 1836. I examine patent assignments for selected inventors for 19 data sets (see table A.2). Whether inventors had assignments was determined from the U.S. Patent Office's "Assignment Index Volumes." These volumes list names of patentees who assigned patents, together with page numbers in which they appear in "Patent Assignment Digests." (Both sets of volumes are kept in National Archives, College Park, Md.) Depending on the letter beginning the last name, one or two index volumes were examined for assignments through 1864. (Volumes for all letters ended in 1864, so rather than beginning the next volumes, I stopped examining assignments in 1864.) The Patent Assignment Digests listed the assignee, the assignor (sometimes a secondary assignment by someone other than the patentee), the date, a short description of the type of patent, and some terms of the contract (such as assigning all or part of the patent and assigning for the country, states, or counties). I typically examined a few assignments per patentee in order to study larger numbers of patentees.

I examined assignments for patentees for whom all patents had been ascertained (listed as technology crossover inventors, all-economy inventors, and individuals and occupations). This procedure determined assignments for any of their patents, not just for the particular technologies, so that engine inventors might have assignments for engines and stoves. I further restricted those examined in three ways. First, I studied only inventors who patented from 1836 through 1860. Because the Assignment Digests typically ended in mid-1864, this allowed at least three and a half years for each patent to be assigned. Second, I studied only letters of the alphabet that had many inventors (though the total was the large majority of inventors). Third, for technology samples I examined only those with known occupations in order to determine whether some occupations assigned patents more frequently than others.

Firm Records and Other Data

Firm records were indispensable for the study (see table A.3). Because of the breadth of industries studied, it was not possible to examine all pertinent firm records. I concentrated on records of machinery firms and foundries associated with textiles, engines, printing presses, machine tools, woodworking, and clocks, often relying on

publications for insights into the records of other firms. In addition, I studied records for a few firms making screws, textiles, and firearms. One patent agent had useful records in the period.

Several sources provided essential information on the distribution of producers and inventors (see table A.4). Many sources provided data on individual firms, which could be used to understand the size and volatility of firms, how commonly firm members invented, and the relation of invention to the location, size, and type of the firm. The Steam Engine Report of 1838 provided disaggregated data on users and producers of stationary engines, boat engines, and locomotives. The Census of 1820 and the McLane Report listed machinery producers; clock, firearms, and other mechanism producers; and lathe users for 1820 and 1831. Census manuscripts for 1850 and 1860 listed over 2,000 machinery and mechanism producers in these years. In addition, data sets of patent agents for dozens of cities from 1845 to 1865, U.S. Paris Exposition winners in 1867, officers of the New York Exhibition in 1853, and Ordnance Department contractors during the Civil War fleshed out a portrait of technological capabilities and accomplishments before 1865.

Table A.1. Patent and Invention Data Sets

Data Sets	Chapter Used	Patenting Period	Individuals Sampled	Patentees	Patents	Patentees, Known Occup.	Selection Method
Technologies: early							
Textiles	2	1790–1835		298	390	52	Keywords, Subject Index of Patents
Steam engineering	2	1790–1835		154	184	44	Keywords, Subject Index of Patents
Printing presses	2	1790–1835		32	41	21	Keywords, Subject Index of Patents
Clocks and Watches	2	1790–1835		36	50	12	Keywords, Subject Index of Patents
Woodworking machines	2	1790–1835		83	90	10	Keywords, Subject Index of Patents
Woodworking: sawmills	2	1790–1835		138	154	—	Keywords, Subject Index of Patents
Firearms	2	1790–1835		52	55	10	Keywords, Subject Index of Patents
Technologies: all		1790–1865					
Textiles	3, 5, 10	1790–1865		878	1,270	264	Keywords, Subject Index of Patents
Steam engineering	3, 5, 10	1790–1865		673	812	263	Keywords, Subject Index of Patents
Printing presses	3, 5, 10	1790–1865		169	267	97	Keywords, Subject Index of Patents
Clocks and watches	3, 5, 10	1790–1865		164	226	70	Keywords, Subject Index of Patents
Woodworking machines	3, 5, 10	1790–1865		393	474	91	Keywords, Subject Index of Patents
Firearms	3, 5,10	1790–1865		545	863	156	Keywords, Subject Index of Patents
Machine tools	5, 10	1790–1865		108	174	80	Keywords, Subject Index of Patents
Bridges	6, 10	1790–1865		125	166	54	Keywords, Subject Index of Patents
Railroad	8, 10	1825–65		411	508	198	Keywords, Subject Index of Patents
Sewing machines	8, 10	1836–65		487	841	—	Patent Office classification
Telegraphs	8, 10	1836–65			178	—	Patent Office classification
Reapers and harvesters	8, 10	1825–65			564	—	Keywords, Subject Index of Patents
Shoe manufacturing	10	1836–65		368	455	81	Patent Office classification
Petroleum	10	1790–1865		107	238	53	Keywords, Subject Index of Patents
Technology Crossover Patents							
Textiles	7, 9	1790–1865		127	338	40	Technology Samples
Steam engineering	7, 9	1790–1865		84	331	41	Technology samples

continued

Table A.1. continued

Data Sets	Chapter Used	Patenting Period	Individuals Sampled	Patentees	Patents	Patentees, Known Occup.	Selection Method
Printing presses	7, 9	1790–1865		118	525	85	Technology samples
Clocks and watches	7, 9	1790–1865		107	343	54	Technology samples
Woodworking machines	7, 9	1790–1865		127	468	63	Technology samples
Firearms	7, 9	1790–1865		121	534	72	Technology samples
Machine tools	5	1836–65		108	451	80	Technology samples
Machine tools	9	1790–1865		131	507	84	Technology samples
Bridges	6, 9	1790–1865		125	367	54	Technology samples
Locomotives	9	1790–1865		119	526	75	Technology samples
Sewing machines	9	1790–1865		121	482	81	Technology samples
Telegraphs	9	1790–1865		90	312	63	Technology samples
Reapers and harvesters	9	1790–1865		68	323	42	Technology samples
Shoe manufacturing	10	1790–1865		81	319	81	Technology samples
Petroleum	10	1790–1865		107	526	53	Technology samples
Augmented Crossovers							
Textiles	11	1836–65		229	1,007	229	Technology samples
Steam engineering	11	1836–65		226	1,131	226	Technology samples
Printing presses	11	1836–65		85	436	85	Technology samples
Clocks and watches	11	1836–65		70	301	70	Technology samples
Woodworking machines	11	1836–65		128	528	128	Technology samples
Firearms	11	1836–65		184	1,145	184	Technology samples
Machine tools	11	1836–65		83	409	83	Technology samples
Bridges	11	1836–65		49	200	49	Technology samples
Railroad	11	1836–65		191	813	191	Technology samples
Sewing machines	11	1836–65		194	995	194	Technology samples
Telegraphs	11	1836–65		66	271	66	Technology samples
Reapers and harvesters	11	1836–65		165	775	165	Technology samples
Shoe manufacturing	11	1836–65		159	529	159	Technology Samples

All Economy							
All inventors	4, 5, 7	1790–1865		748	1,819	366	Annual reports
All inventors	4	1836–1925		228	1,365	—	All inventors, 1836–65
Major innovators	4, 6, 7, 8, 9, 10	1790–1865	340	282	1,911	282	Biographical dictionaries
Major innovators	4	1790–1925		8		8	Major innovators
Occupations and Individuals							
Thomas Edison	1	1869–90		1	532	1	All patents, annual reports
Engine producers, 1838	2	1790–1846	204	60	212	204	Steam engine report of 1838
Machinists	5, 7	1838–65	591	261	1,168	261	Machinery principals, city directories and census manuscripts
Early engineers (before 1836)	6	1790–1846	79	14	57	79	Biographical dictionary
Urban engineers and electricians	6, 7	1790–1865	155	67	312	155	City directories, 1845–65
Franklin Institute leaders	6	1790–1846	67	18	41	67	Officer listings, Franklin Institute
Patent agents	7	1790–1865	166	80	397	166	City directories, 1845–65
Patent examiners	7	1790–1865	76	26	110	76	Listing from various sources
New York Exhibition, 1853	7	1836–54	274	165	—	—	Exhibits in technologies studied
New York Exhibition, 1853	4	—	1,988	—	—	—	All U.S. exhibits except minerals and art

Table A.2. Patent Assignment Studies

Data Sets	Chapter Used	Patenting Period	Individuals Sampled	With Assignments, 1836–64	Selection Method
Technologies					
Textiles	3, 7, 9	1836–60	24	18	Crossover Inventors with Occupations
Steam engineering	3, 7, 9	1836–60	23	15	Crossover Inventors with Occupations
Printing presses	3, 7, 9	1836–60	48	31	Crossover Inventors with Occupations
Clocks and watches	3, 7, 9	1836–60	26	16	Crossover Inventors with Occupations
Woodworking	3, 7, 9	1836–60	49	33	Crossover Inventors with Occupations
Firearms	3, 7, 9	1836–60	32	23	Crossover Inventors with Occupations
Machine tools	5, 9	1836–60	43	30	Crossover Inventors with Occupations
Bridges	6, 9	1836–60	32	13	Crossover Inventors with Occupations
Railroads	8, 9	1836–60	49	30	Crossover Inventors with Occupations
Sewing machines	8, 9	1836–60	41	34	Crossover Inventors with Occupations
Telegraphs	8, 9	1836–60	40	26	Crossover Inventors with Occupations
Reapers and harvesters	8, 9	1836–60	26	21	Crossover Inventors with Occupations
Shoe manufacturing	10	1836–60	39	29	Crossover Inventors with Occupations
All Economy					
All inventors	4, 5, 7	1836–60	300	154	All Inventors
Major innovators	4, 7, 8	1836–65	189	134	Major Innovators
Occupations					
Machinists	5	1836–60	169	101	Machinery Principals
Urban engineers and electricians	6	1836–60	48	33	Urban Engineers and Electricians
Patent agents	7	1836–60	52	35	Patent Agents
Patent examiners	7	1836–60	12	9	Patent Examiners

Table A.3. Firm Records

Firm or Individual	Chapter Used	Content	Importance
Allen, Zachariah	1, 2, 3, 5, 6, 9	Correspondence; autobiography; history of cotton industry	Textiles
Arnold, Aza	3	Correspondence; contracts	Textiles; mechanism
Bancroft, Joseph	2	Correspondence	Textiles
Betts, Mahlon & Seal	5	Orderbooks, correspondence	Foundry and machine shop
Brown & Sharpe	1, 3, 5, 8, 9	Sales, correspondence	Machine tools; precision; sewing machines
Campbell, Andrew	3, 5	Autobiography	Printing presses
Corliss, George	1, 3, 5, 9	Correspondence, orders, financial records	Steam engines
Fairbanks & Bancroft	1, 3	Correspondence; orders	Steam engines
Farmer, Moses	8, 9	Correspondence, financial records	Telegraph, electricity
Fulton, Robert	2	Correspondence	Steamboat; engines
Harvey, Thomas W.	5	Correspondence; biography	Screws
Henry,William & family	2	Sales; orderbooks; contracts	Firearms
Hoe, Richard M. & Co.	3, 5, 10	Correspondence; patents	Printing presses; experimental work
Jenks, Alfred	3	Catalog	Textiles
Jenks, Barton	10	Springfield Armory practice	Textiles; firearms
Jenks, Lemuel P.	7	Correspondence	Patent agent
Kilburn-Lincoln Co.	3, 9	Correspondence; purchases	Textiles; waterwheels
Locks & Canals	1, 3, 5, 9	Inventories, correspondence; employment	Textiles, machine tools
Lowell Machine Shop	3, 5, 9	Employment records	Textiles, locomotives, machine tools
Page, George	3	Catalog; testimonials	Woodworking
Providence Iron Foundry	2	Orderbook; ledger; sales	Foundry; textiles
Sellers,William	5, 8, 10	Orderbook; visitors' register	Machine tools
Terry, Eli	2	Broadside	Clocks
Wood & Mann Steam Engine Co.	10	Catalog; testimonials	Steam engines

Table A.4. Output and Activity Data Sets

Data Sets	Chapter Used	Number Sampled	Content	Selection Method
Steam engine producers, 1838	2, 5, 8, 9	322	Location and output of stationary, boat, and locomotive engine producers	Steam Engine Report of 1838
Steam engine users, 1838	2, 3, 8	1,282	Location and industry of stationary, boat, and locomotive engine users	Steam Engine Report of 1838
Selected manufacturers, 1820	2, 5	340	Location, output, employment	Machinery and mechanism manufacturers, lathe users, Census of 1820
Selected manufacturers, 1831	2, 5	384	Location, output, employment	Machinery and mechanism manufacturers, lathe users, McLane Report
Census manuscripts, 1850	3, 5	960	Products, employment, capital, value	Machinery and mechanism producers, selected counties
Census manuscripts, 1860	3, 5, 8	1,183	Products, employment, capital, value	Machinery and mechanism producers, selected counties
Patent agents	7	173	Location, timing	City and busines directories
Paris Exposition winners, 1867	1, 10	102	U.S. award winners	Paris Exhibiton catalog
New York exhibiton officers, 1853	7	220	Officers and jury members, with occupations	New York Exhibition catalog
Ordnance department contractors	10	150	Civil War firearms manufacturers	Ordnance Department lists

Note: This table contains data sets not given in table A.1.

Chapter 1. Structure and Change

1. James M. Usher, *Paris Universal Exposition; 1867* (Boston: Nation Office, 1868); Angus Maddison, *Dynamic Forces in Capitalist Development: A Long-Run Comparative View* (Oxford: Oxford Univ. Press, 1991), 275; U.S. Department of Commerce, *Historical Statistics of the United States: Colonial Times to 1970* (Washington, D.C.: U.S. Government Printing Office, 1975), pt. 2, 958–59; Merle Curti, "America at the World Fairs, 1851–1893," *American Historical Review* 55 (1950): 833–56.

2. *Science and the Modern World* (New York: Macmillan, 1925), 136.

3. This description of Edison's success draws on Robert Friedel and Paul Israel, with Bernard S. Finn, *Edison's Electric Light: Biography of an Invention* (New Brunswick, N.J.: Rutgers Univ. Press, 1986); Paul Israel, *Edison: A Life of Invention* (New York: John Wiley & Sons, 1998); Matthew Josephson, *Edison: A Biography* (New York: McGraw-Hill, 1959); Thomas P. Hughes, *American Genesis: A Century of Invention and Technological Enthusiasm* (New York: Penguin, 1990), 20–52; Thomas P. Hughes, *Networks of Power: Electrification in Western Society, 1880–1930* (Baltimore: Johns Hopkins Univ. Press, 1983); Francis Jehl, *Menlo Park Reminiscences,* 3 vols. (Dearborn, Mich.: Edison Institute, 1934–41); and the essays in William S. Pretzer, ed., *Working at Inventing: Thomas A. Edison and the Menlo Park Experience* (Baltimore: Johns Hopkins Univ. Press, 2002). Menlo Park is described in Ford R. Bryan, *Henry's Attic: Some Fascinating Gifts to Henry Ford and His Museum* (Dearborn, Mich.: Ford Books, 1995), 21–32. Patents were surveyed in U.S. Patent Office, *Annual Report of the Commissioner of Patents* (Washington, D.C.: Government Printing Office, various years).

4. Paul Israel, "Telegraphy and Edison's Invention Factory," in Pretzer, *Working at Inventing,* 66–83. On the telegraph, see Paul Israel, *From Machine Shop to Industrial Laboratory: Telegraphy and the Changing Context of American Invention, 1830–1920* (Baltimore: Johns Hopkins Univ. Press, 1992). The connection of the telegraph to electrical lighting was not distinctively American; Werner Siemens followed a similar path in Germany.

5. Moreover, the organization and pace of work in Menlo Park was very much that of a machine shop. Governed by a "machine shop culture," it was a community of craftsmen working together, at times raucously for extraordinary periods, for the

common goal of creating a unique product, working prototypes of inventions. The culture distinguished Menlo Park from Edison's West Orange laboratory of the late 1880s and even more from General Electric's Schenectady lab a decade later. Andre Millard, "Machine Shop Culture and Menlo Park," in Pretzer, *Working at Inventing,* 45–65.

6. Israel, *Edison,* 51.

7. Josephson, *Edison,* 62; Israel, "Telegraphy and Edison's Invention Factory," 66–68; Friedel and Israel, *Edison's Electric Light.*

8. "Technological Change in the Machine Tool Industry, 1840–1910," *Perspectives on Technology* (Cambridge: Cambridge Univ. Press, 1976), 9–31.

9. I group knowledge-communicating mechanisms together as institutions because each involved persisting patterns of interaction that were given to individuals and that governed their actions. The patterns were structured by the imperfectness of information, which made knowledge costly to acquire. They may involve norms but could also involve routines without normative importance. Such institutions were organized in different ways. Some were political, such as laws, courts, and public administrative bodies. Others were more economic in nature, organized around occupations and firms. One view, associated with the new institutional economics, conceives an institution more abstractly to be a rule with an enforcement mechanism. In this view a market would not form an institution. One classic statement of this view is Douglass C. North, *Institutions, Institutional Change, and Economic Performance* (Cambridge: Cambridge Univ. Press, 1990). Yet where knowledge was imperfect, individuals needed to acquire knowledge to make market decisions about which machine tool or engineer was best or which employer was hiring, and networks supplied much of this information. Individuals had an incentive to share information if they expected others to share with them or expected their reputation to improve, which relates the two ideas of institutions. We will consider such practices, incentives, and punishments over the course of this book.

10. Brown & Sharpe, *A Brown and Sharpe Catalogue Collection* (Mendham, N.J.: Astragal, 1997); David A. Hounshell, *From the American System to Mass Production, 1800–1932* (Baltimore: Johns Hopkins Univ. Press, 1984), 75–82; Brown & Sharpe Manufacturing Co., Records, 1833–1994 (Providence: Rhode Island Historical Society).

11. Louis C. Hunter, *A History of Industrial Power in the United States, 1780–1930,* vol. 2: *Steam Power* (Charlottesville: Univ. Press of Virginia, 1985), 263–83 (hereafter cited as *Steam Power*); [Locks and Canals] Proprietors of the Locks and Canals on Merrimack River, Records, 1792–1947 (Baker Library, Harvard Business School, Boston), "Letter Books," DA1-6; George H. Corliss, Papers, 1835–1962 (Brown Univ., John Hay Library, Providence, R.I.); Business Correspondence, boxes 17–20 (the Corliss papers include Fairbanks and Bancroft correspondence); Nathan Rosenberg and Manuel Trajtenberg, "A General-Purpose Technology at Work: The Corliss Steam Engine in the Late Nineteenth-Century United States," *Journal of Economic History* 64 (March 2004): 61–99.

12. Although Allen's engine-making business failed, he did contribute to technological knowledge through his six textile patents and his important book *The Sci-*

ence of Mechanics, which documented methods of machine design and construction. Zachariah Allen, Papers, 1767–1946 (Rhode Island Historical Society, Providence), "Autobiography," Correspondence (box 1, ser. 1), and "Zachariah Allen on Steam Engines," box 1; Hunter, *Steam Power,* 277–79, 709–12; Zachariah Allen, *The Science of Mechanics* (Providence, R.I.: Hutchens & Cory, 1829).

13. David Wilkinson, "Reminiscences," in *The New England Mill Village, 1790–1860,* ed. Gary Kulik, Roger Parks, and Theodore Z. Penn (Cambridge, Mass.: MIT Press, 1982); Zachariah Allen Papers, box 3; Joseph W. Roe, *English and American Tool Builders* (New Haven, Conn.: Yale Univ. Press, 1916); Edwin A. Battison, *Screw-Thread Cutting by the Master-Screw Method since 1480. Contributions from the Museum of History and Technology.* Bulletin 240, paper 37 (Washington, D.C.: Smithsonian Institution, 1964).

14. Giovani Dosi, Christopher Freeman, Gerald Silverberg, and Luc Soete, eds., *Technical Change and Economic Theory* (London: Pinter Publishers, 1988); Richard R. Nelson, ed., *National Innovation Systems* (New York: Oxford Univ. Press, 1993); Bengt-Ake Lundvall, ed., *National Systems of Innovation* (London: Pinter, 1992); Daniele Archibugi and Jonathan Michie, eds., *Technology, Globalization, and Economic Performance* (Cambridge: Cambridge Univ. Press, 1997).

15. Thomas Jefferson, *Writings of Thomas Jefferson,* ed. Albert Ellery Bergh (Washington, D.C.: Thomas Jefferson Memorial Association, 1907), 13:333–34.

16. Karl Marx, *Capital: A Critique of Political Economy* (New York: Vintage, 1977), 1:616–17. On uncertainty and asymmetric information, see Richard R. Nelson and Sidney G. Winter, *An Evolutionary Theory of Economic Change* (Cambridge, Mass.: Belknap Press of Harvard Univ. Press, 1982); Nathan Rosenberg, "Uncertainty and Technological Change," in *The Mosaic of Economic Growth,* ed. Ralph Landau, Timothy Taylor, and Gavin Wright (Stanford: Stanford Univ. Press, 1996), 334–53. For an application of asymmetric information to the history of the U.S. firm, see Naomi R. Lamoreaux, Daniel M. G. Raff, and Peter Temin, "Beyond Markets and Hierarchies: Toward a New Synthesis of American Business History," *American Historical Review* 108 (2003). On the universality of technology and its spread, see Edwin T. Layton Jr., "Mirror-Image Twins: The Communities of Science and Technology," in *Nineteenth-Century American Science: A Reappraisal,* ed. George H. Daniels (Evanston, Ill.: Northwestern Univ. Press, 1972), 210–30; Rosenberg, "Technological Change in the Machine Tool Industry"; Ross Thomson, "Transformational Growth and the Universality of Technology," in *Growth, Distribution and Effective Demand,* ed. George Argyrous, Matthew Forstater, and Gary Mongiovi (Armonk, N.Y.: M. E. Sharpe, 2003); and Joel Mokyr, *The Gift of Athena: Historical Origins of the Knowledge Economy* (Princeton: Princeton Univ. Press, 2002).

17. John K. Brown, *The Baldwin Locomotive Works, 1831–1915* (Baltimore: Johns Hopkins Univ. Press, 1995); Hounshell, *From the American System to Mass Production;* Philip Scranton, *Endless Novelty: Specialty Production and American Industrialization, 1865–1925* (Princeton: Princeton Univ. Press, 1997).

18. Carlyle equated the Mechanical Age with the "Age of Machinery." Thomas Carlyle, "Signs of the Times," *Critical and Miscellaneous Essays* (New York: Scribner, Welford & Co., 1872), 2:233.

Chapter 2. Paths of Initial Mechanization, 1790–1835

1. If a broader set of innovations were considered, the variety of innovation paths would have been wider yet. Studies of civil engineering, the telegraph, and petroleum later in the book will illustrate such innovations.

2. Lance E. Davis, Richard A. Easterlin, and William N. Parker, *American Economic Growth: An Economist's History of the United States* (New York: Harper & Row, 1972), 19–25; David W. Galenson, "The Settlement and Growth of the Colonies: Population, Labor, and Economic Development," in *The Cambridge Economic History of the United States,* ed. Stanley L. Engerman and Robert E. Gallman (Cambridge: Cambridge Univ. Press, 2000) 1:135–207; Robert A. Margo, "The Labor Force in the Nineteenth Century," in *The Cambridge Economic History of the United States,* ed. Stanley L. Engerman and Robert E. Gallman (Cambridge: Cambridge Univ. Press, 2000), 2:209.

3. Jeremy Atack and Peter Passell, *A New Economic View of American History from Colonial Times to 1940,* 2nd ed. (New York: Norton, 1994), 30–51; James F. Shepherd and Gary M. Walton, *Shipping, Maritime Trade and the Economic Development of Colonial North America* (Cambridge: Cambridge Univ. Press, 1972).

4. Jacob E. Cooke, ed., "Report on Manufactures," *The Reports of Alexander Hamilton* (New York: Harper & Row, 1964), 143–45, 147–52, 166–78; Drew R. McCoy, *The Elusive Republic: Political Economy in Jeffersonian America* (Chapel Hill: Univ. of North Carolina Press, 1980). On wealth and markets, see Galenson, "The Settlement and Growth of the Colonies," 189–207; Winifred Rothenberg, "The Market and Massachusetts Farmers, 1750–1855," *Journal of Economic History* 41 (1981): 283–314. Productivity could increase without mechanization through craft specialization and the putting out system, though scarce labor and limited markets formed barriers to such change. Still, the nonmechanized workshop did increase productivity early in the nineteenth century. Kenneth L. Sokoloff, "Was the Transition from the Artisanal Shop to the Nonmechanized Factory Associated with Gains in Efficiency? Evidence from the U.S. Manufacturing Censuses of 1820 and 1850," *Explorations in Economic History* 21 (1984): 351–82.

5. Galenson, "Settlement and Growth of the Colonies," 193; Davis, *American Economic Growth,* 147–50; Richard R. John, *Spreading the News: The American Postal System from Franklin to Morse* (Cambridge: Harvard Univ. Press, 1995), 4, 25–63.

6. On the antebellum patent system, see Edward C. Waltersheid, *To Promote the Progress of Useful Arts: American Patent Law and Administration, 1798–1836* (Littleton, Col.: Fred B. Rothman, 1998); B. Zorina Khan, *The Democratization of Invention: Patents and Copyrights in American Economic Development, 1790–1920* (Cambridge: Cambridge Univ. Press, 2005).

7. Cooke, "Report on Manufactures," 197. Arthur H., Cole, ed., *Industrial and Commercial Correspondence of Alexander Hamilton* (New York: Augustus Kelley, 1968), 7–8. Emphasis in the original.

8. Cooke, "Report on Manufactures," 130, 196; Cole, *Industrial and Commercial Correspondence,* 72.

9. Cooke, "Report on Manufactures," 194; McCoy, *Elusive Republic,* 159–65. Hamil-

ton does not expressly claim that government support was universally applicable, but the principles he advances suggest wide applicability. He may have moderated tariffs to increase federal government revenues; see Douglas A. Irwin, "The Aftermath of Hamilton's 'Report on Manufactures,'" *Journal of Economic History* 64 (September 2004): 800–821. The workshops of the French Royal Manufactures provided models of government manufacturing.

10. Cooke, "Report on Manufactures," 184; Silvio A. Bedini, *Thinkers and Tinkers: Early American Men of Science* (New York: Charles Scribner's Sons, 1975); David A. Hounshell, *From the American System to Mass Production, 1800–1932* (Baltimore: Johns Hopkins Univ. Press, 1984); Merritt Roe Smith, "Army Ordnance and the 'American System' of Manufacturing, 1815–61," in *Military Enterprise and Technological Change,* ed. Merritt Roe Smith (Cambridge, Mass.: MIT Press, 1985), 39–86. One reason for a strong governmental role was the limited effectiveness of armament production during the Revolutionary War; see Neil L. York, *Mechanical Metamorphosis* (Westport, Conn.: Greenwood Press, 1985).

11. Bedini, *Thinkers and Tinkers.* On industrial aspects of Enlightenment thought, see Joel Mokyr, *The Gift of Athena: Historical Origins of the Knowledge Economy* (Princeton: Princeton Univ. Press, 2002). Paine's well-regarded bridge could span 500 feet but proved too expensive to build. He would be better known as the author of "Common Sense" and *The Rights of Man.* Thomas Jefferson, *The Life and Selected Writings of Thomas Jefferson,* ed. Adrienne Koch and William Peden (New York: Random House, 1944), 467; York, *Mechanical Metamorphosis,* 197.

12. Cole, *Industrial and Commercial Correspondence,* 19, 25, 33, 34, 53, 80–88.

13. In writing Whitney to grant his patent, Jefferson noted: "As the state of Virginia . . . carries on household manufactures of cotton to a great extent, as I also do myself, and one of our great embarrassments is the clearing the cotton of the seed, I feel a considerable interest in the success of your invention for family use." One reason Jefferson so supported invention was that he felt it would aid in family production. Jefferson, *Life and Selected Writings,* 526–27.

14. Oliver Evans, *The Young Mill-Wright and Miller's Guide,* 9th ed. (Philadelphia: Carey, Lea & Blanchard, 1836), 203. On Jefferson's use and patent payment, see Thomas Jefferson, *The Writings of Thomas Jefferson,* ed. Albert Ellery Bergh (Washington, D.C.: Thomas Jefferson Memorial Association, 1907), 337.

15. U.S. Treasury Department, Third Census, 1810, *A Statement of the Arts and Manufactures of the United States for the Year 1810,* in *American State Papers* (Washington, D.C.: Gales & Seaton, 1832), 6:690–712; [Louis McLane], *Documents Relative to the Manufactures in the United States* (1833; rpt., New York: Augustus M. Kelley, 1969). Samuel Slater was the Rhode Island enumerator in 1831.

16. David J. Jeremy, *Transatlantic Industrial Revolution: The Diffusion of Textile Technologies between Britain and America, 1790–1830s* (Cambridge Mass: MIT Press, 1981).

17. Cole, *Industrial and Commercial Correspondence,* 62, 73; Jeremy, *Transatlantic Industrial Revolution,* 36–47.

18. Cole, *Industrial and Commercial Correspondence,* 73. Textiles were made in

four steps. Ginned cotton was prepared for spinning by carding, which cleaned and straightened it. It was then spun into yarn or thread, which involved spinning machines (of which the jenny, Arkwright's water frame, and the mule were the alternatives) and auxiliary machines. In the final steps, not yet mechanized, thread was woven and finished.

19. Joseph W. Roe, *English and American Tool Builders* (New Haven, 1916), 121; Caroline F. Ware, *The Early New England Cotton Manufacture* (Boston: Houghton Mifflin, 1931), 123–25; Geo. S. White, *Memoir of Samuel Slater* (New York: Kelley, 1967); David Wilkinson, "Reminiscences," in *The New England Mill Village, 1790–1860*, ed. Gary Kulik, Roger Parks and Theodore Z. Penn (Cambridge, Mass.: MIT Press, 1982); Jeremy, *Transatlantic Industrial Revolution.*

20. Cole, *Industrial and Commercial Correspondence,* 72–73; White, *Memoir of Samuel Slater;* Ware, *Early New England Cotton Manufacture,* 123–25; Wilkinson, "Reminiscences"; Jeremy, *Transatlantic Industrial Revolution.*

21. Jeremy, *Transatlantic Industrial Revolution,* 76–91.

22. Brooke Hindle and Steven Lubar, Engines *of Change: The American Industrial Revolution, 1790–1860* (Washington, D.C.: Smithsonian Institution, 1986); Roe, *English and American Tool Builders*; Jeremy, *Transatlantic Industrial Revolution,* 39, 77–87; Albert Gallatin, "Manufactures: Communicated to the House of Representatives, April 19, 1810," in *American State Papers* (Washington, D.C.: Gales & Seaton, 1832), 6:425–39; Barbara M. Tucker, *Samuel Slater and the Origins of the American Textile Industry, 1790–1860* (Ithaca, N.Y.: Cornell Univ. Press, 1984); Ware, *Early New England Cotton Manufacture.* David Meyer offers the most complete discussion of textile and textile machinery networks in *Networked Machinists: High-Technology Industries in Antebellum America* (Baltimore: Johns Hopkins Univ. Press, 2006), 50–72. Immigrants who diffused woolen textile production, particularly John Scholfield and his family, depended more on other British immigrants due in part to the considerable skill required to card, spin, and weave wool. Jeremy, *Transatlantic Industrial Revolution,* 118–37.

23. Some argue that Slater's conservatism contributed to his decline through his slow adoption of mule spinning and the power loom (Tucker, *Samuel Slater*). He did use mule-spinning machines, though they were not central to his operations or to those of many early firms. He adopted the power loom by 1818, only shortly after Waltham's success, and formed a steam mill, an iron foundry, and a machinery firm. James L. Conrad Jr., "'Drive That Branch': Samuel Slater, the Power Loom, and the Writing of America's Textile History," in *Technology and American History,* ed. Stephen H. Cutcliffe and Terry S. Reynolds (Chicago: Univ. of Chicago Press, 1997), 45–72.

24. Jeremy, *Transatlantic Industrial Revolution,* 149. In addition, 58 generic machinists immigrated from 1809 through 1813 and 848 from 1824 through 1831, some with experience in textiles. Output data from Robert Zevin, "The Growth of Cotton Textile Production after 1815," in *The Reinterpretation of American Economic History,* ed. Robert Fogel and Stanley Engerman (New York: Harper & Row, 1971). The trade disruptions benefited textiles, and the postwar Tariff of 1816 retained some of the protection. Yet mechanization had progressed far enough that English imports could not sweep

away U.S. producers. Joseph H. Davis and Douglas A. Irwin, "Trade Disruptions and America's Early Industrialization" (NBER Working Paper, 2005). On whether the need for tariffs to protect the industry lasted until 1830 or 1865, see Douglas A. Irwin and Peter Temin, "The Antebellum Tariff on Cotton Textiles Revisited," *Journal of Economic History* 61 (September 2001): 777–98; and C. Knick Harley, "The Antebellum Tariff: Different Products or Competing Sources? A Comment on Irwin and Temin," *Journal of Economic History* 61 (September 2001): 799–805.

25. Jeremy, *Transatlantic Industrial Revolution,* 99–100; George S. Gibb, *The Saco-Lowell Shops: Textile Machinery Building in New England, 1813–1949* (Cambridge: Harvard Univ. Press, 1950); Ware, *Early New England Cotton Manufacture,* 81, 301–2.

26. Jeremy, *Transatlantic Industrial Revolution,* 99–100; Gibb, *Saco-Lowell Shops;* Ware, *Early New England Cotton Manufacture,* 81, 301–2; Naomi R. Lamoreaux, *Insider Lending: Banks, Personal Connections, and Economic Development in Industrial New England* (Cambridge: Cambridge Univ. Press, 1994). Alfred Chandler associated Lowell's advantages with the rise of the managerial capitalism, though he saw its significance more in production than in managerial organization. *The Visible Hand: The Managerial Revolution in American Business* (Cambridge, Mass.: Belknap Press, 1977), 67–72. See also Zevin, "Growth of Cotton Textile Production"; and John W. Lozier, *Taunton and Mason: Cotton Machinery and Locomotive Manufacture in Taunton, Massachusetts, 1811–61* (New York: Garland, 1986), 16–18. Philip Scranton describes a differently organized system in *Proprietary Capitalism: The Textile Manufacture at Philadelphia, 1800–1885* (Cambridge: Cambridge Univ. Press, 1983).

27. Jeremy, *Transatlantic Industrial Revolution,* 98; Lozier, *Taunton and Mason;* Scranton, *Proprietary Capitalism;* Anthony F. C. Wallace, *Rockdale: The Growth of an American Village in the Early Industrial Revolution* (New York: Knopf, 1978). At times *Gilmour* is spelled *Gilmore.*

28. Alexander Everett, *Journal of the Proceedings of the Friends of Domestic Industry and British Opinions on the Protecting System* (New York: Garland, 1974), 112; Jeremy, *Transatlantic Industrial Revolution,* 277–78; Zevin, "Growth of Cotton Textile Production"; Ware, *Early New England Cotton Manufacture;* Rolla M. Tyron, *Household Manufactures in the United States, 1640–1860* (Chicago: Univ. of Chicago Press, 1917).

29. Zachariah Allen, "Cotton Manufacture in the United States," Papers, 1767–1946 (Rhode Island Historical Society, Providence), MS, box 3, n.d.; Wilkinson, "Reminiscences," 95.

30. Mobility was not always upward; Wilkinson was bankrupted in 1829 and moved widely thereafter. Wilkinson, "Reminiscences"; Conrad, "'Drive That Branch'"; Roe, *English and American Tool Builders;* Robert S. Woodbury, "History of the Lathe to 1850," *Studies in the History of Machine Tools* (Cambridge, Mass.: MIT Press, 1972), 89–93; Edwin A. Battison, *Screw-Thread Cutting by the Master-Screw Method since 1480, Contributions from the Museum of History and Technology,* bulletin no. 240, paper 37 (Washington, D.C.: Smithsonian Institution, 1964).

31. Wilkinson also proposed to adapt his screw-cutting lathe to make Slater's machinery, but Slater refused and brought in a British mechanic to build one. According to Wilkinson, the attempt failed. Wilkinson, "Reminiscences"; Gary Kulik and Patrick

Malone, "The Wilkinson Mill," American Society of Mechanical Engineers, 1977; Jeremy, *Transatlantic Industrial Revolution;* Tucker, *Samuel Slater.*

32. The communications network spanned regions. The Delaware textile manufacturer Joseph Bancroft corresponded with several textile machinery manufacturers, including William Leonard in Matteawan and Pitcher and Brown in Providence. Joseph Bancroft & Sons, "Letter Book" (Hagley Museum and Library, Wilmington, Del.).

33. Gibb, *Saco-Lowell Shops,* 11–90. According to Gibb, Perkins recommended Moody to Francis Lowell.

34. Meyer, *Networked Machinists,* 50–72.

35. McLane, *Documents Relative to the Manufactures;* Zevin, "Growth of Cotton Textile Production." See also Robert B. Zevin, *The Growth of Manufacturing in Early Nineteenth Century New England* (New York: Arno, 1975).

36. Gibb, *Saco-Lowell Shops,* 49, 635–36.

37. Providence Iron Foundry, "Ledgers, 1817–1832" and "Order Books, 1826–1832" (Slater Collection, Baker Library, Harvard Business School, Boston). Customers usually had their own machine tools, but in one case the foundry offered to rent its lathes, drilling machines, and other equipment.

38. Zevin, "Growth of Cotton Textile Production"; U.S. Treasury Department, *Statement of the Arts and Manufactures,* 694; McLane, *Documents Relative to the Manufactures.*

39. Jeremy, *Transatlantic Industrial Revolution,* 177–78; Carroll Pursell, *The Machine in America* (Baltimore: Johns Hopkins Univ. Press, 1995), 46–49; Gallatin, *Manufactures,* 436.

40. The relation of patents to invention and innovation will be discussed more fully in chaps. 4 and 7.

41. The parallel of patents and factory production was incomplete because production grew from 1810 to 1820, but patents did not. The textile sample was drawn from a keyword search of the cumulative classification of patents issued through 1873, a method chosen to secure a consistent data set through 1865. Keyword searches never catch all patents (such as Pliny Earle's, which was indexed as "pricking leather, for cards"). A check of all textile patents through 1846 indicates that this procedure accurately reflected the complete population.

42. Among surveyed patents, 48 percent were for spinning and related operations, 36 percent for weaving, 11 percent for carding, and 6 percent for other operations. The share of weaving inventions is probably overstated.

43. Occupational data only approximate network status. As noted, some of those with occupations listed as machinists actually were in textile networks but were not counted as such. On the other hand, weavers or spinners might have used traditional methods entirely separate from Industrial Revolution techniques, which would overstate the share in networks communicating the new technology. The latter problem is especially difficult for crafts in which new and old technologies coexisted, such as woodworking, clockmaking, and gunsmithing. Finally, different networks coexisted in the same industry; methods in the Lowell system differed from those in the Rhode

Island–southern Massachusetts system, and both differed from the Philadelphia-area methods.

44. Those positioned to gain use include those listed in city directories with network occupations and another 13 that, according to industry sources, had network occupations, mostly as mill owners or managers. These added inventors were not included in occupational totals to avoid biases in favor of network inventors.

45. The occupational distribution mirrored Britain's, where patents listed the inventor's occupation. In the corresponding period textile manufacturers and machinists received over three-quarters of textile patents, though manufacturers received a larger share than in the United States. Jeremy, *Transatlantic Industrial Revolution,* 55–56. A more complete determination of occupations probably would increase the share of inventors outside textiles and textile machinery.

46. Andrew Ure, *The Cotton Manufacture of Great Britain* (London: Charles Knight, 1836), 2:67; Samuel Batchelder, *Introduction and Early Progress of the Cotton Manufacture in the United States* (Boston: Little, Brown, 1963); Jeremy, *Transatlantic Industrial Revolution,* 178.

47. Quote from Gibb, *Saco-Lowell Shops,* 79–80; Louis C. Hunter, *A History of Industrial Power in the United States, 1780–1930,* vol. 1: *Waterpower in the Century of the Steam Engine* (Charlottesville: Univ. Press of Virginia, 1979), 462–71. In 1838 one mill reported that it used engines "only in case of a deficiency of water during long droughts, or a heavy press of business." U.S. Treasury Department, "Steam-Engine," 25th Cong., 3rd sess. (serial no. 345), H. Doc. 21. (1839), 57; Theodore Steinberg, *Nature Incorporated: Industrialization and the Waters of New England* (Amherst: Univ. of Massachusetts Press, 1991).

48. Aza Arnold letter to Zachariah Allen, 1861, in Zachariah Allen, "Correspondence," Papers, 1767–1946; ser. 1, box 1; Jeremy, *Transatlantic Industrial Revolution.*

49. Thomas Jefferson, *Papers,* ed. Julian P. Boyd (Princeton: Princeton Univ. Press, 1954), 10:400–401. The nation-binding effects became more pressing after Jefferson's Louisiana Purchase.

50. Carroll W. Pursell Jr., *Early Stationary Steam Engines in America* (Washington, D.C.: Smithsonian Institution, 1969); G. N. von Tunzelmann, *Steam Power and British Industrialization to 1860* (Oxford: Oxford Univ. Press, 1978); James T. Flexner, *Steamboats Come True* (Boston: Little, Brown, 1978); Darwin H. Stapleton, "Benjamin Henry Latrobe and the Transfer of Technology," in *Technology in America,* ed. Carroll W. Pursell Jr. (Cambridge, Mass.: MIT Press, 1981).

51. Louis C. Hunter, *A History of Industrial Power in the United States, 1780–1930,* vol. 2: *Steam Power* (Charlottesville: Univ. Press of Virginia, 1985); Pursell, *Early Stationary Steam Engines;* David P. Billington, *The Innovators: The Engineering Pioneers Who Made America Modern* (New York: John Wiley & Sons, 1996).

52. Benjamin H. Latrobe, "First Report," *Transactions of the American Philosophical Society* 6 (1804): 89–98.

53. Quoted in Greville Bathe and Dorothy Bathe, *Oliver Evans* (Philadelphia: Historical Society of Pennsylvania, 1935), 90. *The Abortion of the Young Steam Engineer's Guide* (Philadelphia: Fry & Kammerer), which Evans published in 1805, listed as ap-

plications flour milling, sawing timber, pumping water, pressing sugarcane, metal rolling and forging, raising coal, distilling, papermaking, turning lathes, grinding, and moving boats and carriages (viii, ix).

54. Bathe and Bathe, *Oliver Evans;* Eugene S. Ferguson, *Oliver Evans: Inventive Genius of the American Industrial Revolution* (Greenville, Del.: Hagley Museum, 1980), 36–51.

55. "Mars Works," *Aurora General Advertiser,* November 19, 1808; Bathe and Bathe, *Oliver Evans,* 70; Ferguson, *Oliver Evans.*

56. Louis C. Hunter, *Steamboats on the Western Rivers* (Cambridge: Harvard Univ. Press, 1949), 179–83.

57. Pursell, *Early Stationary Steam Engines,* 51–53.

58. Ferguson, *Oliver Evans;* Pursell, *Early Stationary Steam Engines.*

59. Quoted in Bathe and Bathe, *Oliver Evans,* 172.

60. Billington, *Innovators;* Flexner, *Steamboats Come True,* 208–316; Pursell, *Early Stationary Steam Engines;* Hunter, *Steamboats;* Hunter, *Steam Power.*

61. Other engine inventors enjoyed similar benefits, including John Stevens, a graduate of King's College (now Columbia University) and a student of natural philosophy versed in steam engineering principles. Likewise, Rumsey interacted with Washington, Jefferson, Franklin, the Philadelphia scientific establishment, Watt, and British scientists. Flexner, *Steamboats Come True;* Ferguson, *Oliver Evans.*

62. Pursell, *Early Stationary Steam Engines,* 28–32, 44, 51, quote on 24. That many worked along similar lines suggests that no one was indispensable. Had Fulton and Livingston's steamboat not succeeded, Livingston's cousin John Stevens might well have become the leader. Evans was the most unique, but Richard Trevithick invented the functional equivalent of Evans's machine in Britain about the same time. Still, Fulton sped up steamboat development in the United States, and it would have taken a considerable time before Trevithick's engine, which was located in Cornwall, reached the United States.

63. Communication in a technological community could lead in the wrong direction. Franklin's judgments led Rumsey and Fitch toward pump-driven jet propulsion and away from paddlewheels. Moreover, failure may attend even the best contacts. Going to England to buy an engine and hire mechanics, Rumsey so impressed Boulton and Watt that they offered him a partnership in developing steamboats. Foolishly, Rumsey demanded unacceptable terms. Rather than working with the outstanding steam engineers of the time, he redesigned his British patent specifications to get around the Boulton and Watt patent and failed to acquire production skills to build adequate steamboats. Brooke Hindle, *Emulation and Invention* (New York: NYU Press, 1981); Flexner, *Steamboats Come True.*

64. Expansion was rapid after 1831, though we do not know how rapid. Only 11 percent of the 2,000 stationary engines operating in 1838 had been constructed before 1830, but because most of the machines used in 1831 appear to have been abandoned by 1838, engine growth cannot be known with any precision. Hunter, *Steam Power,* 70, 74; Peter Temin, "Steam and Waterpower in the Early Nineteenth Century," *Journal of Economic History* 26 (June 1966): 189; Jeremy Atack, Fred Bateman, and Thomas Weiss,

"The Regional Diffusion and Adoption of the Steam Engine in American Manufacturing," *Journal of Economic History* 40 (1980): 285; Hunter, *Steamboats,* 33.

65. Fulton to Littleton W. Tazewell, February 26, 1814, Robert Fulton Papers, 1765–1815 (New York: New York Public Library).

66. Bathe and Bathe, *Oliver Evans,* 207; "A Great Discovery," *Niles Weekly Register,* n.s. 1, August 30, 1817, 5–7; Flexner, *Steamboats Come True,* 341–45.

67. American publications on the steam engine included Latrobe, "First Report," and a detailed 1813 series in the *Emporium of Arts and Sciences,* ed. scientist Thomas Cooper (n.s. 1 [1813]).

68. *The Troy Directory, for 1830* (Troy, N.Y.: Tuttle & Gregory, 1830), 70.

69. Archibald D. Turnbull, *John Stevens* (New York: Century Co., 1928), 344; Pursell, *Early Stationary Steam Engines,* 103.

70. U.S. Treasury Department, "Steam-Engine"; Hunter, *Steam Power;* Temin, "Steam and Waterpower."

71. Author's calculations based on U.S. Treasury Department, "Steam-Engine"; Hunter, *Steam Power,* 76–82. Stationary steam engine usage lagged behind Britain. In 1838 the Lancashire cotton industry alone used almost as much stationary power as did the entire United States, and the industry throughout the United Kingdom used perhaps 65 percent more than the United States did. Other industries added greatly to Britain's advantage. Mines and textiles were the most important uses of British engines; they accounted for 75 percent of the horsepower employed around Glasgow in 1825. By contrast, in the United States in 1838 these two amounted to about 11 percent by number of engines and 16 percent by horsepower. Von Tunzelmann, *Steam Power and British Industrialization,* 76–80, 236; "Steam Engines," *Journal of the Franklin Institute* 1 (February 1826): 108. On Evans, see Bathe and Bathe, *Oliver Evans,* 207.

72. Southern shares would be a bit higher if all Louisville's output were included. Louisville was the only important southern center, due in part to its proximity to Pittsburgh and Cincinnati. Southern firms were much smaller, averaging under two-fifths as many stationary engines and under one-fifth as many boat engines as the nation as a whole.

73. Hunter, *Steamboats,* 106.

74. McLane, *Documents Relative to the Manufactures,* 2:239–54; U.S. Treasury Department, "Steam-Engine." Pittsburgh was the only city to provide such detail.

75. U.S. Department of State, *Census of the United States (1820), Digest of Accounts of Manufacturing Establishments in the United States and of Their Manufactures* (Washington, D.C.: Gales & Seaton, 1823) entries 1282, 1292; U.S. Treasury Department, "Steam-Engine."

76. Part of the low invention in the West was due to its late start in engine making, which began around 1815. But even after 1815 it had less than 20 percent of patents.

77. Patents were ascertained from Edmund Burke, *List of Patents for Inventions and Designs, Issued by the United States, from 1790 to 1847* (Washington, D.C.: J. & G. S. Gideon, 1847). Only 54 percent of patentees held steam engine or navigation patents, but because firms sold a wide range of products, other patents pertained to the firms' product lines.

78. Hunter, *Steam Power.*

79. Bathe and Bathe, *Oliver Evans,* 157; Hunter, *Steam Power,* 308–99.

80. Louis C. Hunter, "The Heroic Theory of Invention," in *Technology and Social Change in America,* ed. Edwin T. Layton Jr. (New York: Harper & Row, 1973), 25–46; quote on 25.

81. Quote from *Abortion of the Young Steam Engineer's Guide,* viii, ix. Some boats also added a second engine. Hunter, *Steamboats,* 122–29; 133–53.

82. Hunter, *Steamboats,* 22–27, 52–59, 190–205, 374; James Mak and Gary M. Walton, "Steamboats and the Great Productivity Surge in River Transportation," *Journal of Economic History* 32 (September 1972): 619–39. On federal involvement in western infrastructure, see Lawrence J. Malone, *Opening the West: Federal Internal Improvements before 1860* (Westport, Conn.: Greenwood, 1998).

83. Lawrence C. Wroth, *The Colonial Printer* (Charlottesville: Univ. Press of Virginia, 1964); A. E. Musson, "Newspaper Printing in the Industrial Revolution," *Economic History Review* 10 (1957–58): 411–26; S.N.D. North, "History and Present Condition of the Newspaper and Periodical Press of the United States," *Tenth Census of the United States, 1880,* vol. 8 (Washington, D.C.: Government Printing Office, 1883); Chauncey M. Depew, ed., *1795–1895: One Hundred Years of American Commerce* (New York: D. O. Haynes, 1895), 1:166–73, 2:314–19.

84. Frank E. Comparato, *Chronicles of Genius and Folly: R. Hoe & Company and the Printing Press as a Service to Democracy* (Culver City, Calif.: Labyrinthos, 1979); Rollo G. Silver, *The American Printer, 1787–1825* (Charlottesville: Univ. Press of Virginia, 1967); Rollo G. Silver, *Typefounding in America, 1787–1825* (Charlottesville: Univ. Press of Virginia, 1965).

85. After securing some sales in the United States, Clymer moved to Britain, where he manufactured the machine for European use. Silver, *American Printer;* Comparato, *Chronicles of Genius and Folly;* Ferguson, *Oliver Evans.*

86. Treadwell also introduced small jobbing presses. James Moran, *Printing Presses: History and Development from the Fifteenth Century to Modern Times* (Berkeley: Univ. of California Press, 1973); Comparato, *Chronicles of Genius and Folly;* Robert Hoe, *A Short History of the Printing Press* (New York: Robert Hoe, 1902).

87. Comparato, *Chronicles of Genius and Folly,* 41.

88. Comparato, *Chronicles of Genius and Folly,* 16; Moran, *Printing Presses,* 123; Stephen O. Saxe, *American Iron Hand Presses* (New Castle, Del.: Oak Knoll Books, 1992); Silver, *American Printer.*

89. Robert Willis, "Machines and Tools for Working in Metal, Wood, and Other Materials," *Lectures on the Results of the Great Exhibition of 1851* (London: David Bogue, 1852); Hindle, *Emulation and Invention.* Clockmakers at times contributed to scientific advance, such as the Philadelphian David Rittenhouse.

90. On the definition of mass production and its relation to nineteenth-century technology, see Hounshell, *From the American System to Mass Production,* 1–13.

91. John J. Murphy, "Entrepreneurship in the Establishment of the American Clock Industry," *Journal of Economic History* 26 (June 1966): 169–86; Donald R. Hoke, *Ingenious Yankees: The Rise of the American System of Manufactures in the Private Sector* (New York: Columbia Univ. Press, 1990); Kenneth D. Roberts, *Eli Terry and the*

Connecticut Shelf Clock (Bristol, Conn.: Ken Roberts, 1973); Penrose R. Hoopes, "Early Clockmaking in Connecticut," in *Tercennary Commission of the State of Connecticut,* no. 20 (New Haven, Conn.: Yale Univ. Press, 1934).

92. Murphy, "Entrepreneurship"; Hoke, *Ingenious Yankees.* On the imprecision of early gear cutting, see Robert S. Woodbury, "History of the Gear-Cutting Machine," *Studies in the History of Machine Tools* (Cambridge, Mass.: MIT Press, 1972).

93. Quoted in Hoopes, "Early Clockmaking," 12; Eli Terry, *Clocks, Made by Eli Terry, for Levi C. and E Porter, and Warranted, if Cased and Well Used* (Waterbury, Conn., ca. 1808, available in Hagley Museum); Hoke, *Ingenious Yankees.*

94. Terry's workers moved widely through Connecticut and elsewhere; one set up shop in Cincinnati through the help of other Connecticut clockmakers. Hoopes, "Early Clockmaking"; Murphy, "Entrepreneurship"; Roberts, *Eli Terry;* Hoke, *Ingenious Yankees;* McLane, *Documents Relative to the Manufactures,* 992–95.

95. David S. Landes, *Revolution in Time: Clocks and the Making of the Modern World* (Cambridge, Mass.: Belknap Press, 1983).

96. Cole, *Industrial and Commercial Correspondence,* 53; U.S. Census Office, *Seventh Census of the United States, 1850,* vol. 2: *Manufactures in the Several States and Territories for the Year Ending June 1, 1850,* Senate Executive Document, 35th Cong., 2nd sess., no. 39 (Washington, D.C., 1858;) Nathan Rosenberg, *Perspectives on Technology* (Cambridge: Cambridge Univ. Press, 1976), 34.

97. John Richards, *A Treatise on the Construction and Operation of Wood-working Machines* (London: E. & F. N. Spon, 1872); Robert Grimshaw, *Saws* (Philadelphia: E. Claxton, 1882); Edwin T. Freedley, *Philadelphia and Its Manufactures* (Philadelphia: E. Young, 1867); Victor S. Clark, *History of Manufactures in the United States, 1607–1860* (Washington, D.C.: Carnegie Institution, 1916), 421–22; Rosenberg, *Perspectives on Technology,* 32–49; Comparato, *Chronicles of Genius and Folly;* Henry Disston & Sons, *The Saw in History* (Philadelphia: Keystone Saw, Tool, Steel and File Works, 1915).

98. Charles F. Hummel, *With Hammer in Hand* (Charlottesville: Univ. of Virginia Press, 1968); C. R. Tompkins, *A History of the Planing Mill* (New York: John Wiley & Sons, 1889); Carolyn C. Cooper, "A Patent Transformation: Woodworking Mechanization in Philadelphia, 1830–1856," in *Early American Technology: Making and Doing Things from the Colonial Era to 1850,* ed. Judith A. McGaw (Chapel Hill: Univ. of North Carolina Press, 1994), 278–327; Rosenberg, *Perspectives on Technology,* 32–49.

99. Spinning wheel firms were smaller yet, with $240 in capital and under three workers. Carriage and wagon firms were larger but still averaged only about $2,500 in capital. U.S. Department of State, *Census of the United States (1820), Digest of Accounts of Manufacturing Establishments.*

100. Carolyn C. Cooper, *Shaping Invention: Thomas Blanchard's Machinery and Patent Management in Nineteenth-Century America* (New York: Columbia Univ. Press, 1991); Cooper, "Patent Transformation."

101. McLane, *Documents Relative to the Manufactures,* 1:498–99. It is unclear how Josiah Fay related to Jerub Fay, also of Worcester, who was a leader in mortising machines in the antebellum period. Richards, *Treatise;* Dana M. Batory, *Vintage Woodworking Machinery* (Mendham, N.J.: Astragal Press, 1997).

102. John Richards, a British woodworker familiar with American techniques, suggested that Samuel Bentham was such a revolutionary figure. He developed a system of woodworking machines used in penitentiaries supervised by his ever-utilitarian brother Jeremy, and then equipped the royal shipyards with his famous block-making machinery. His machines were ingenious but did not lead to widespread diffusion. Richards argues that British woodworking was largely stagnant and that more innovations came from the United States. Richards, *Treatise,* 49.

103. Richards, *Treatise,* 37–39; Cooper, "Patent Transformation."

104. Determined from returns from U.S. Department of State, *Census of the United States (1820), Digest of Accounts of Manufacturing Establishments.*

105. David A. Hounshell, *From the American System to Mass Production;* Felicia Johnson Deyrup, *Arms Makers of the Connecticut Valley: A Regional Study of the Economic Development of the Small Arms Industry, 1798–1870,* Smith College Studies in History (Northampton, Mass.) 33 (1948).

106. Quotes, respectively, from Roe, *English and American Tool Builders,* 134; and Hounshell, *From the American System to Mass Production*, esp. 26; Smith, "Army Ordnance."

107. Smith, "Army Ordnance."

108. Deyrup, *Arms Makers,* 37–41. An example of failure is chronicled in the business records of William Henry. See "Sales Records," "Manufactures of the Bolton Gun Works," and "Order Books," Henry Family, Papers, 1758–1909 (Hagley Museum and Library, Wilmington, Del.).

109. Eli Whitney was once seen as the key innovator, but he was less innovative than North. Yet he was an effective publicist and trained innovators, including Roswell Lee, who later superintended the Springfield Armory, and James Carrington, who inspected arms. Hounshell, *From the American System to Mass Production,* 25–50; Merritt Roe Smith, *Harpers Ferry Armory and the New Technology* (Ithaca, N.Y.: Cornell Univ. Press, 1977); Deyrup, *Arms Makers,* 37–42. On the limits of Whitney's role, see Robert S. Woodbury, "The Legend of Eli Whitney and Interchangeable Parts," *Technology and Culture* 1 (Summer 1960): 235–53; and Merritt Roe Smith, "John H. Hall, Simeon North, and the Milling Machine: The Nature of Innovation among Antebellum Arms Makers," *Technology and Culture* 14 (October 1973): 573–91.

110. In the first systematic examination of interchangeable production, Charles Fitch wrote: "General accounts of machinery remarkable in design and precise in operation can be construed to signify little more than drills and boring and slabbing machines of a rude description." "Interchangeable Mechanism," in U.S. Census Office, *Tenth Census, 1880*, *Report on the Manufactures of the United States at the Tenth Census, 1880* (Washington, D.C.: Government Printing Office, 1883), 2.

111. Deyrup, *Arms Makers,* 240; Cooper, *Shaping Invention,* 17–20.

112. Quoted in Fitch, "Interchangeable Mechanism," 3. After having divided labor into 55 specialties in 1816, Harpers Ferry added only nine by 1825, while Springfield had grown to 100. Smith, *Harpers Ferry Armory*. See also James Biser Whisker, *The United States Armory at Harper's Ferry, 1799–1860* (Lewiston, N.Y.: Edwin Mellen, 1997). On Philadelphia techniques, see James J. Farley, *Making Arms in the Machine*

Age: Philadelphia's Frankford Arsenal, 1816–1870 (University Park: Pennsylvania State Univ. Press, 1994).

113. Michael H. Best, *The New Competition: Institutions of Industrial Restructuring* (Cambridge: Harvard Univ. Press, 1990), 43; Deyrup, *Arms Makers,* 66–67; Smith, "Army Ordnance."

114. Smith, *Harpers Ferry Armory*. Mobility was quite extensive. Harpers Ferry master armorer Marine Wickham, for example, became an important arms inspector and consultant at the national armories and then a private contractor in Philadelphia and an importer with contracts at both armories.

115. In 1827 Hall received a patent for "cutting metallic substances," but because the patent was lost, we do not know what it covered. Deyrup, *Arms Makers;* Claude Blair, ed., *Pollard's History of Firearms* (New York: Macmillan, 1983); Smith, *Harpers Ferry Armory.*

116. Private producers did not uniformly prosper; by the 1820s only a few contractors had repeat contracts. Virginia's state armory went out of business, and after his government shipments were rejected, William Henry Jr. made muskets for private demand and state militias and a few hundred annually for Astor's American Fur Co., but no more for the federal government. Henry Family, "Order Books," Papers; Deyrup, *Arms Makers;* Giles Cromwell, *The Virginia Manufactory of Arms* (Charlottesville: Univ. Press of Virginia, 1975).

117. Fitch, "Interchangeable Mechanism," 5, 14; Smith, *Harpers Ferry Armory.*

118. Alexis de Tocqueville, *Democracy in America,* 2 vols. (New York: Knopf, 1945), 2:165.

119. In this sense technologies for various industries converged. Rosenberg, *Perspectives on Technology,* 9–31.

120. One might note that mechanization affected nontechnological factors, which indirectly connected innovation paths. Falling textile prices and transportation improvements contributed to per capita income growth and market integration, steamboats and steam engines helped tap resources, and industry groups were potent lobbyists about patent and tariff policy. Yet mechanization was only beginning and to that extent was just starting to drive economic growth and transformation. Marx once remarked about England that "today, industrial supremacy brings with it commercial supremacy. In the period of manufacture it is the reverse: commercial supremacy produces industrial predominance. *Capital: A Critique of Political Economy* (London: Vintage, 1976), 1:918. Similarly, agricultural and commercial expansion was fundamental to U.S. development in the period.

Chapter 3. Ongoing Mechanization, 1836–1865

1. Even if patents failed, they could have affected innovation and productivity if learning from them identified routes to avoid, suggested limits to overcome, or provided expertise in patenting. That unimportant inventions fostered major inventions was consistent with the experience of Evans, Fulton, Terry, and Blanchard. Many innovations were not patented; chaps. 4 and 7 discuss the relation of patented and unpatented innovations.

2. Assignments were examined through mid-1864 rather than through 1865 for convenience because assignment indexes for all inventors ended at that time. I examined those who patented from 1836 through 1860, which allowed each patent at least several years to receive assignments. Assignors included both the inventor and, especially when patents were assigned by territory, the inventor's assignees.

3. To study wider numbers of patentees, I typically examined only a few assignments per inventor; had more been examined, the share with internal assignments would have risen modestly.

4. The share of inventors with known occupations rose from 21 percent before 1835 to 32 percent after 1835 because more cities had directories, somewhat more inventors were urban, and census manuscripts in 1850 and 1860 listed occupations for two-fifths of post-1835 inventors with known occupations. The shifting occupational shares between periods in part reflects the inclusion of census manuscript sources in the 1836–65 period, which had higher shares in trade, service, and agriculture. Without this source machinists would have had the same share between periods and trade and service inventors would have fallen even more.

5. As noted earlier, the network share may have been larger because many listed as machinists were parts of networks, though patenting by industry occupations not integrated into innovative networks (such as carpenters for mortising inventions) would have the opposite effect. Why the network share declined in several sectors is unclear; the greater detail of earlier city directory entries was one factor.

6. U.S. Census Office, *Eighth Census of the United States, 1860,* vol. 3: *Manufactures of the United States in 1860* (Washington, D.C.: Government Printing Office, 1865), ix.

7. Jeremy Atack and Peter Passell, *A New Economic View of American History from Colonial Times to 1940* (New York: Norton, 1994), 181–82; Henry Louis Stettler III, *Growth and Fluctuations in the Ante-Bellum Textile Industry* (New York: Arno, 1977), 25, 37, 48, 94, 243; Alexander Everett, *Journal of the Proceedings of the Friends of Domestic Industry and British Opinions on the Protecting System* (New York: Garland, 1974), 112; [Louis McLane], *Documents Relative to the Manufactures in the United States* (1833; rpt., New York: Augustus M. Kelley, 1969), 1:1045 (also called the McLane Report).

8. U.S. Census Office, *Eighth Census,* esp. 3:758. The value of textile machinery was larger than that reported. As census manuscripts reveal (considered more fully in chap. 5), some firms made textile machinery in addition to other machinery. Two of the largest firms—the Lowell Machine Shop and William Mason—were not listed as textile machinery producers because each made other machines. The Lowell Machine Shop employed 300 workers to make many kinds of machines and was grouped with generic machinery producers. William Mason and Co. made $250,000 in textile machines, along with locomotives valued at $80,000. On the other hand, some classified as textile machinery firms also made other goods.

9. McLane, *Documents Relative to the Manufactures;* U.S. Census Office, *Eighth Census,* esp. vol. 3. This figure probably underestimates the growth of cotton textile machinery output because firms such as the Lowell Machine Shop were classified as generic machinery firms in 1860 but not in 1831.

10. John W. Lozier, *Taunton and Mason: Cotton Machinery and Locomotive Manufacture in Taunton, Massachusetts, 1811–1861* (New York: Garland, 1986), 388. For an example of firms making wide ranges of machinery, see [Alfred] Jenks & Son, *Illustrated Catalogue of Machines Built by Alfred Jenks & Son* (Bridesburg, Pa. [1853], in Hagley Museum and Library, Wilmington, Del.).

11. [Locks and Canals] Proprietors of the Locks and Canals on Merrimack River, Records, 1792–1947 (Baker Library, Harvard Business School, Boston), "List of Hands Employed," RF1; George S. Gibb, *The Saco-Lowell Shops: Textile Machinery Building in New England, 1813–1949* (Cambridge: Harvard Univ. Press, 1950), 53; David R. Meyer, *Networked Machinists: High-Technology Industries in Antebellum America* (Baltimore: Johns Hopkins Univ. Press, 2006), 45–46. Meyer and Lozier provide the best accounts of textile networks.

12. Many early patentees complained of patent infringement, such as Aza Arnold, who required years to get Locks and Canals to license his patents. Aza Arnold, Papers (Rhode Island Historical Society, Providence), Correspondence.

13. Karl Marx, *Capital: A Critique of Political Economy* (London: Vintage, 1976), 1:563.

14. Matteawan also imported and manufactured the English fly frame in the 1830s. Joseph W. Roe, *English and American Tool Builders* (New Haven, Conn.: Yale Univ. Press, 1916), 59–61; Lozier, *Taunton and Mason,* 169–70, 245–71.

15. [Locks and Canals], Records, FB1, 111 ff., and "Letter Books," DA1, July 14, 1838; Gibb, *Saco-Lowell Shops,* 81–82; Louis C. Hunter, *A History of Industrial Power in the United States, 1780–1930,* vol. 2: *Steam Power* (Charlottesville: Univ. Press of Virginia, 1985), 205–7 (hereafter cited as *Steam Power*).

16. Jonathan Thayer Lincoln, "Material for a History of American Textile Machinery: The Kilburn-Lincoln Papers," *Journal of Economic and Business History* 4 (February 1932): 259–80; Kilburn, Lincoln Machine Co., Business Records, 1835–1929 (Baker Library, Harvard Business School, Boston); Louis C. Hunter, *A History of Industrial Power in the United States, 1780–1930,* vol. 1: *Waterpower in the Century of the Steam Engine* (Charlottesville: Univ. Press of Virginia, 1979), 305–32 (hereafter cited as *Waterpower*).

17. Why foreign firms assigned patents rather than exporting patented equipment is unclear. In the case of Roberts the initiative to patent came from an American firm. Lozier, *Taunton and Mason,* 268–69.

18. Lozier, *Taunton and Mason,* 256–85.

19. The ring spinner spun tougher yarn than the cap spinner. Lozier, *Taunton and Mason,* 204–42; Gibb, *Saco-Lowell Shops,* 649.

20. William Crompton went to Britain, where his machine gained some use, but he felt prospects were better in the United States. William Mass, "Developing and Utilizing Technological Leadership: Industrial Research, Vertical Integration, and Business Strategy at the Draper Company, 1816–1930," *Business and Economic History* 18 (1989): 129–30; Lozier, *Taunton and Mason,* 172–77; J. Leander Bishop, *A History of American Manufactures from 1608 to 1860* (Philadelphia: E. Young, 1868), 2:542–43.

21. Lozier, *Taunton and Mason,* 183–95.

22. *Journal of the Franklin Institute* 23 (1839): 398.

23. Gibb, *Saco-Lowell Shops,* 78, 745.

24. Paul A. David, *Technical Choice, Innovation, and Economic Growth: Essays on American and British Experience in the Nineteenth Century* (London: Cambridge Univ. Press, 1975), 174–91. The differential gear, which was introduced to existing Lowell machines in the 1820s, exemplifies how new techniques modified installed machinery. On the spread of the differential gear, see David J. Jeremy, *Artisans, Entrepreneurs and Machines: Essays on the Early Anglo-American Textile Industries, 1770–1840s* (Aldershot, Hampshire: Ashgate Publishing, 1998), chap. 10. For an interpretation that productivity in the Lowell plant increased due to the intensification of the work of a changing workforce, see William Lazonick and Thomas Brush, "The 'Horndal Effect' in Early U.S. Manufacturing," *Explorations in Economic History* 22 (1985): 53–96.

25. Burke, *List of Patents for Inventions and Designs,* 40; Bishop, *History,* 3:397–99; Lozier, *Taunton and Mason,* 146; Gibb, *Saco-Lowell Shops,* 108, 636.

26. Hunter, *Waterpower,* 328–63.

27. Hunter, *Steam Power,* 106–8; Lozier, *Taunton and Mason.*

28. Holmes may have brought milling machines when he moved to the Hadley Falls Co. in Holyoke, Mass.; an 1860 inventory included milling machines along with 200 lathes and the complement of boring machines, planers, and drill presses used by the best shops. Gibb, *Saco-Lowell Shops,* 138; Thomas R. Navin, *The Whitin Machine Works since 1831* (Cambridge: Harvard Univ. Press, 1950), 48; Lozier, *Taunton and Mason,* 275–76.

29. Oliver Evans, *The Abortion of the Young Steam Engineer's Guide* (Philadelphia: Fry & Kammerer, 1805), 1.

30. Hunter, *Steam Power,* 384, 110–12. Steam engines were used more by larger establishments. If mines and waterworks were included, the advantage of stationary engines was greater yet.

31. U.S. Treasury Department, "Steam-Engine"; U.S. Census Office, *Census of the United States (1870),* vol. 3: *The Statistics of the Wealth and Industry of the United States* (Washington, D.C.: Government Printing Office, 1872), 392, 456, 615; Hunter, *Steam Power,* 78–79. The South's 6,100 engines in 1870 had declined to 15 percent of all engines.

32. Hunter, *Steam Power,* 247.

33. *The Boston Directory. For the Year Commencing July 1, 1860* (Boston: Adams, Sampson & Co., 1860), 71 (advertising department). Some firms developed special-use engines, such as Wood and Mann's portable steam engines, which were mounted on wheels. The firm listed 63 distinct uses for its engine in 23 states, and made machinery for many of these uses, including woodworking, sugar mills, cotton gins, metal cutting, and oil wells. *The Wood and Mann Steam Engine Company, Builders of Their Celebrated Patent Portable Steam Engines* (Utica, N.Y.: Curtis & White, 1866).

34. These counties included over half of all machinery firms with almost two-thirds of employees. See U.S. Census Office, "Manufacturing Manuscripts from the Eighth Census, 1860" (national archives and state archives in Conn., Del., Md., N.H., N.J., N.Y.); U.S. Census Office, "Manufacturing Manuscripts from the Seventh Census, 1850" (national archives and state archives in Conn., Del., Md., N.H., N.J., N.Y.).

35. George H. Corliss, Papers, 1835–1962, Business Correspondence, box 17 (Brown University, John Hay Library, Providence, R.I.).

36. Firms listing the number and value of machines averaged almost 18 machines. If their average price of $2,200 per machine applied to others, surveyed engine makers averaged about 17 machines in 1860. Because larger firms were oversampled, average output was somewhat less.

37. "On the Relative Proportions of the Various Parts of the Boulton and Watt's, or Low Pressure, Steam Engine," *Journal of the Franklin Institute* 3 (1827): 336–37.

38. The timing of patenting did not parallel that of sales; sales grew fastest early in the period, but patenting was constant before taking off after 1855.

39. Zachariah Allen, "Autobiography," in Papers, 1767–1946 (Providence: Rhode Island Historical Society, n.d.); Zachariah Allen, *The Science of Mechanics* (Providence, R.I.: Hutchins & Cory, 1829).

40. Quoted in Hunter, *Steam Power,* 264; Richard L. Hills, *Power from Steam: A History of the Stationary Steam Engine* (Cambridge: Cambridge Univ. Press, 1989), 178–82; Robert H. Thurston, *A History of the Growth of the Steam-Engine* (New York: D. Appleton, 1878); Robert H. Thurston, *Stationary Steam Engines. Simple and Compound: Especially as Adapted to Electric Lighting Purposes,* 2nd ed. (New York: J. Wiley & Sons, 1888).

41. Corliss, Papers, Correspondence, folder 2, boxes 17–20; Ross Thomson, *The Path to Mechanized Shoe Production in the United States* (Chapel Hill: Univ. of North Carolina Press, 1989); Hunter, *Steam Power;* Carroll W. Pursell Jr., *Early Stationary Steam Engines in America* (Washington, D.C.: Smithsonian Institution, 1969), 127.

42. Hunter, *Steam Power,* 263–66; Phillip Scranton, *Endless Novelty: Specialty Production and American Industrialization, 1865–1925* (Princeton: Princeton Univ. Press, 1997), 36–38; Lozier, *Taunton and Mason;* Nathan Rosenberg and Manuel Trajtenberg, "A General-Purpose Technology at Work: The Corliss Steam Engine in the Late-Nineteenth-Century United States," *Journal of Economic History* (March 2004): 61–99. Corliss also secured revenue from several licensees making his patented machines.

43. Hunter, *Steam Power,* 273–76; Thurston, *Stationary Steam Engines,* 317–18.

44. Hunter, *Steam Power,* 325, 450–62; Hills, *Power from Steam,* 170, 192–203.

45. *Dictionary of American Biography;* Hunter, *Steam Power;* Lance Day and Ian McNeil, *Biographical Dictionary of the History of Technology* (London: Routledge, 1996), 13.

46. Hunter, *Steam Power,* 285, 281.

47. Proprietors of the Locks and Canals, Records, FB1, 111 ff.; DA1, July 14, 1838, Scranton, *Endless Novelty,* 36; Corliss, Papers, box 4, file 6a.

48. Hunter, *Steam Power,* 280.

49. Quotes respectively from Bishop, *History,* 3:382; and Hunter, *Steam Power,* 281.

50. Bishop, *History,* esp. 27. Merrick and Towne played a primary role in spreading the steam hammer in the United States after James Nasmyth, the celebrated British engineer and Maudslay's one-time assistant, assigned them his patent. Brown & Sharpe, *A Brown and Sharpe Catalogue Collection* (Mendham, N.J.: Astragal, 1997), 19–27.

51. Hunter, *Steam Power,* 264.

52. Hunter, *Steam Power;* James Mak and Gary M. Walton, "Steamboats and the Great Productivity Surge in River Transportation," *Journal of Economic History* 32 (September 1972): 619–39.

53. At least 240 steamboat explosions in the United States had taken over 1,800 lives through 1848, three-quarters on western rivers; western steamboat explosions took another 1,155 lives from 1848 through 1852. Oliver Evans recognized the problem when one of his engines exploded, but private activity did not solve it. Inventors designed boilers, gauges and safety valves to avoid explosions, alarms to warn of explosions, and construction changes to reduce the impact of explosions, including a safety guard by Oliver Evans's son Cadwallader. These inventions seldom gained much use; steamboat owners and masters often operated with defective boilers, disabled safety valves, and untrained labor. The Franklin Institute addressed the problem in the 1820s; in a sustained, scientifically directed set of experiments from 1830 to 1836, partly supported by the federal government, it illuminated the factors leading to explosions and recommended regulations of steamboat equipment and usage. After decades of ineffective legislation, an 1852 federal act began a process that would largely solve the problem by controlling boiler design, mandating inspection, licensing engineers, and investigating accidents. Louis C. Hunter, *Steamboats on the Western Rivers* (Cambridge: Harvard Univ. Press, 1949), 121–205, 287, 520–46; John G. Burke, "Bursting Boilers and the Federal Power," in *Technology and American History,* ed. Stephen H. Cutcliffe and Terry S. Reynolds (Chicago: Univ. of Chicago Press, 1997); Bruce Sinclair, *Philadelphia's Philosopher Mechanics: A History of the Franklin Institute, 1824–1865* (Baltimore: Johns Hopkins Univ. Press, 1974). The federal government also helped navigation by removing snags, though efforts to deepen channels fell into abeyance until after the Civil War.

54. Quoted, respectively, from Alexis de Tocqueville, *Democracy in America* (New York: Knopf, 1945), 2:2, 121; and Nathan Rosenberg, ed., *The American System of Manufactures* (Edinburgh: Edinburgh Univ. Press, 1969), 389.

55. Frank Luther Mott, *A History of American Magazines, 1850–1865* (Cambridge: Cambridge Univ. Press, 1938); U.S. Census Office, *Eighth Census,* vol. 3.

56. James Moran, *Printing Presses: History and Development from the Fifteenth Century to Modern Times* (Berkeley: Univ. of California Press, 1973), 78–81, 113–18, 144–49, 178–89; Frank E. Comparato, *Chronicles of Genius and Folly: R. Hoe & Company and the Printing Press as a Service to Democracy* (Culver City, Calif.: Labyrinthos, 1979); *R. Hoe & Co.'s List of Prices* (New York: Charles Shields, 1854), 10–20; Robert Hoe, *A Short History of the Printing Press* (New York: Robert Hoe, 1902), 27–37.

57. Richard M. Hoe and Co., Records, 1824–1953, Columbia University, Letterbooks, 1842–46, February 2 and 13, 1844.

58. Hoe, Records, Letterpress book, 1834–58, Letterbooks, 1839–41, 838, 850, 868, 875, Letterbooks, 1842–46, L box 21, 520; Comparato, *Chronicles of Genius and Folly,* 53, 68–69, 154–57.

59. Andrew Campbell, Papers, 1840–1926 (Hagley Museum and Library, Wilmington, Del.), "Autobiography."

60. Comparato, *Chronicles of Genius and Folly,* 359–65; 1860 manufacturing census

manuscripts. Some competitors succeeded, including Taylor, Campbell, and Gordon. Seth and Isaac Adams sold 70 machines for $140,000 in 1850; Hoe bought the firm for $151,000, $100,000 of which was the estimated value of Adams's patents.

61. John J. Murphy, "Entrepreneurship in the Establishment of the American Clock Industry," *Journal of Economic History* 26 (June 1966): 185; Penrose R. Hoopes, "Early Clockmaking in Connecticut," in *Tercennary Commission of the State of Connecticut,* no. 20 (New Haven, Conn.: Yale Univ. Press, 1934), 19–25; Chauncey Jerome, *History of the American Clock Business for the Past Sixty Years, and Life of Chauncey Jerome, Written by Himself* (New Haven, Conn.: F. C. Dayton, 1860); "The Waterbury Brass Mills," *Scientific American* 8, May 30, June 13, and June 20, 1863, 338–39, 372–73, 388–89; Kenneth D. Roberts, *The Contributions of Joseph Ives to Connecticut Clock Technology, 1810–1862* (Bristol, Conn.: American Clock and Watch Museum, 1970); Roe, *English and American Tool Builders,* 231–38; Rosenberg, *American System of Manufactures,* 341–42; Eric Bruton, *The History of Clocks and Watches* (London: Little, Brown, 1979), 158–61. Roberts and Bruton effectively counter Chauncey Jerome's claim to have invented the 30-hour clock movement; many others, including Jerome's brother Noble, in fact contributed.

62. In an 1856 letter Brown and Sharpe wrote: "The imperfections of the [wire] gauge in common use are known to all engaged in the manufacture, sale, or use of wire; indeed so little reliance is placed upon it that we are informed orders are now generally given by sample. As no improvement can be effected in reference to this matter without the cooperation of the principal manufacturers, dealers and consumers, we respectfully solicit your attention to the subject and to the plan we propose." Recognizing the need for uniformity, early the next year Waterbury Brass Association concurred, resolving "that we will adopt said gauge, and be governed by it, in rolling our metals, and will use our exertions to have it come into general use, as the Standard U.S. Gauge." They then bought several dozen gauges. Brown & Sharpe Manufacturing Co., Records, folder 13.

63. Charles W. Moore, *Timing a Century: History of the Waltham Watch Company* (Cambridge: Harvard Univ. Press, 1945), 6–30, quotes on 13; Henry G. Abbott, *History of the American Waltham Watch Company of Waltham, Mass.* (Chicago: American Jeweler, 1905); Donald R. Hoke, *Ingenious Yankees: The Rise of the American System of Manufactures in the Private Sector* (New York: Columbia Univ. Press, 1990), 180–95. For a contemporary account of the plant, see "The Factory of the American Watch Company," *Scientific American* 8, April 11, 1863, 225–27.

64. Moore, *Timing a Century,* 31–69, 230–31; Abbott, *History,* Hoke, *Ingenious Yankees,* 191–205; David S. Landes, *Revolution in Time: Clocks and the Making of the Modern World* (Cambridge, Mass.: Belknap Press, 1983), 313–20. The Elgin plant is described in detail in Albert D. Richardson, *Making Watches by Machinery* (N.p.p., 1870? [available at the Hagley Library, Wilmington, Del.]), 1–16. By 1868 five watch and clock companies purchased Brown & Sharpe universal milling machines, and six firms bought screw machines. Brown & Sharpe, *Brown and Sharpe Catalogue Collection,* 19–27.

65. Moore, *Timing a Century,* 224.

66. Rosenberg, *American System of Manufactures,* 343–48.

67. Nathan Rosenberg, *Perspectives on Technology* (Cambridge: Cambridge Univ. Press, 1976), 34–43; John Richards, *A Treatise on the Construction and Operation of Wood-working Machines* (London: E. & F. N. Spon, 1872); "On the Working of Wood," *American Polytechnic Journal* 1 (January–June 1853): 100–103; James Elliott Defebaugh, *History of the Lumber Industry of America,* 2 vols. (Chicago: American Lumberman, 1906).

68. Ibid.; Dana M. Batory, *Vintage Woodworking Machinery* (Mendham, N.J.: Astragal Press, 1997), 1–15. The value of using census manuscripts is clear here because published census listed only two woodworking firms.

69. Carolyn C. Cooper, *Shaping Invention: Thomas Blanchard's Machinery and Patent Management in Nineteenth-Century America* (New York: Columbia Univ. Press, 1991), 169–233. Carolyn C. Cooper, "Woodworking Mechanization in Philadelphia, 1830–1856," in *Early American Technology: Making and Doing Things from the Colonial Era to 1850,* ed. Judith A. McGaw (Chapel Hill: Univ. of North Carolina Press, 1994), 293–316.

70. Assignment data from records at the National Archives; George Page, *George Page, Machinist and Manufacturer* (Baltimore: Samuel Sands, 1842) (available in Hagley Museum and Library, Wilmington, Del.).

71. Felicia Johnson Deyrup, *Arms Makers of the Connecticut Valley,* Smith College Studies in History (Northampton, Mass.) 33 (1948): 117–29, 233, 220–21; Merritt Roe Smith, *Harpers Ferry Armory and the New Technology* (Ithaca, N.Y.: Cornell Univ. Press, 1977), 342–44.

72. Deyrup, *Arms Makers,* 17–29; Lewis Winant, *Early Percussion Firearms: A History of Early Percussion Firearms Ignition—from Forsyth to Winchester .44/40* (New York: William Morrow, 1959).

73. Surveyed patents essentially all were for product improvements. The relatively low network share was due in part to the variety of occupations of Civil War inventors; without them two-fifths of inventors were in networks. Half the patents were issued during the war, but, except for the decline of the South, regional shares did not change much. Network inventors were virtually all gunsmiths; only one was listed as a machinist.

74. David A. Hounshell, *From the American System to Mass Production, 1800–1932* (Baltimore: Johns Hopkins Univ. Press, 1984), 46–50; William Hosley, *Colt: The Making of an American Legend* (Amherst: Univ. of Massachusetts Press, 1996), 15–27, 42.

75. Quoted from Rosenberg, *American System of Manufactures,* 142; see also 66–72, 129–44; Merritt Roe Smith, "John H. Hall, Simeon North, and the Milling Machine: The Nature of Innovation among Antebellum Arms Makers," *Technology and Culture* 14 (October 1973): 573–91; Deyrup, *Arms Makers,* 147–59; Charles Fitch, "Interchangeable Mechanism," in U.S. Census Office, Tenth Census, 1880; *Report on the Manufactures of the United States at the Tenth Census* (Washington, D.C.: Government Printing Office, 1883), 5–29; Hounshell, *From the American System to Mass Production,* 44–45; Robert B. Gordon, "Who Turned the Mechanical Ideal into Mechanical Reality?" in *Technology and American History: A Historical Anthology from Technology and*

Culture, ed. Stephen H. Cutliffe and Terry S. Reynolds (Chicago: Univ. of Chicago Press, 1997), 129–64.

76. Smith, "John H. Hall," 588–91; Merritt Roe Smith, "Army Ordnance and the 'American System' of Manufacturing, 1815–1861," in *Military Enterprise and Technological Change,* ed. Merritt Roe Smith (Cambridge, Mass.: MIT Press, 1985), 39–86.

77. Roe, *English and American Tool Builders,* 174–75, 188–97; Meyer, *Networked Machinists,* chap. 9; Deyrup, *Arms Makers,* 182–96; Smith, "John H. Hall," 589.

78. On the risks associated with innovation, including the dangers of inertia, see W. Paul Strassmann, *Risk and Technological Innovation: American Manufacturing Methods during the Nineteenth Century* (Ithaca, N.Y.: Cornell University Press, 1959).

79. "Technological Change in the Machine Tool Industry, 1840–1910," *Perspectives on Technology* (Cambridge: Cambridge Univ. Press, 1976), 9–31.

Chapter 4. Contours of Innovation

1. Nathan Rosenberg, ed., *The American System of Manufactures* (Edinburgh: Edinburgh Univ. Press, 1969), 329–89, quote on 331. Whitworth's colleague, George Wallis, noted other areas of innovation.

2. Jeremy Atack, "Economies of Scale and Efficiency Gains in the Rise of the Factory in America, 1820–1900," in *Quantity and Quiddity: Essays in U.S. Economic History,* ed. Peter Kirby (Middletown, Conn.: Wesleyan Univ. Press, 1987), 296.

3. If the focus was extended to all forms of innovations, not just technological innovation, the effects on production and productivity would be greater yet. Schumpeter identified five forms of innovations: new techniques, new products, new markets, new forms of organization, and new sources of materials. Joseph A. Schumpeter, *The Theory of Economic Development* (New York: Oxford Univ. Press, 1961), 65–66. Organizational changes increased productivity in the putting-out system and in manufactories (i.e., nonmechanized shops bringing many workers together). Kenneth L. Sokoloff, "Was the Transition from the Artisanal Shop to the Nonmechanized Factory Associated with Gains in Efficiency? Evidence from the U.S. Manufacturing Censuses of 1820 and 1850," *Explorations in Economic History* 21 (1984): 351–82. New products such as the steamboat or railroad enabled regional specialization.

4. Chap. 7 will address more fully the relation of inventions, patents and exhibits.

5. The shares of early-industrializing sectors explored in chaps. 2 and 3 were even smaller because the reported shares include all nautical devices, not simply steamboats, knitting and other textile inventions, specialized woodworking equipment, bookbinding and other publication implements, and military equipment beyond firearms.

6. Entries at industrial expositions provide another measure, though the criterion for accepting entries was less coherent than for patents, and exhibition data are less useful to examine trends. For an insightful use of such data, see Petra Moser, "How Do Patent Laws Influence Innovation? Evidence from Nineteenth-Century World's Fairs," *American Economic Review* 95 (September 2005): 1214–36. On the usefulness

of patent data, see Zvi Griliches, "Patent Statistics as Economic Indicators: A Survey," *Journal of Economic Literature* 28 (1990): 1661–1707.

7. See the appendix for details. The sample drew 188 inventors from the 1790–1835 period and 560 from 1836 through 1865. It included 455 inventors sampled from Patent Office annual reports for the years 1847 through 1865 and 294 patentees from 1790 through 1846 taken from a cumulative list of patents (one patentee appeared in both).

8. Kenneth L. Sokoloff and B. Zorina Khan, "The Democratization of Invention during Early Industrialization: Evidence for the United States, 1790–1846," *Journal of Economic History* 50 (June 1990): 363–78. See also B. Zorina Khan, *The Democratization of Invention: Patents and Copyrights in American Economic Development, 1790–1920* (Cambridge: Cambridge Univ. Press, 2005).

9. On postbellum patenting by the all-inventor sample and major innovators, see Ross Thomson, "Inventors and Technological Communication: Toward an Understanding of U.S. Patenting, 1797–1925" (MS, Burlington, Vt., 1996). In the early 1840s the share of inventors with multiple patents began to rise. Sokoloff and Khan note that relatively few patentees before 1842 continued patenting past 1846 ("The Democratization of Invention," 367–68n). I noticed much the same. Of surveyed pre-1835 inventors, only one received patents after 1846.

10. Kenneth L. Sokoloff, "Inventive Activity in Early Industrial America: Evidence from Patent Records, 1790–1846," *Journal of Economic History* 48 (December 1988): 813–50. Aggregate output measures were not closely correlated with patenting. Using Berry's data, the growth of patenting was not much greater in years above the trend compared to years below the trend. Likewise, patenting was not tightly related to trends in industrial production, as measured by Joseph Davis's series, even with reasonable lags of patents behind output. For Berry's data, see Jeremy Atack and Peter Passell, *A New Economic View of American History from Colonial Times to 1940* (New York: Norton, 1994), 16–17; Joseph H. Davis, "An Annual Index of U.S. Industrial Production, 1790–1915," *Quarterly Journal of Economics* 119 (November 2004): 1177–1215. Yet GNP and industrial production data do not directly measure market integration, which probably was more pertinent to inventors. Changing Patent Office standards also affected patents issued, first by decreasing them when patents had to meet strong originality standards after 1836 and then increasing the share of applications accepted when the "liberalizers" controlled the Patent Office about 1857. Wartime patents would have declined more had standards not been relaxed. Robert C. Post, "'Liberalizers' versus 'Scientific Men' in the Antebellum Patent Office," *Technology and Culture* 17 (January 1976): 24–54.

11. Inventors with occupations were biased a bit toward urban inventors and repeat inventors, who had more chances to be observed, which explains why their 2.08 average patents exceeded the 1.72 for all inventors.

12. Physicians were the largest scientific or inventive occupations and constituted nearly half of inventors from this group. Engineers and patenting professions were much less numerous but invented in higher proportions.

13. Patentees not reporting occupations were disproportionately rural, where primary-sector occupations were more common. Still, if occupations for all patentees

were known, primary-sector workers probably constituted no more than one-tenth of inventors, with a smaller share of patents. Robert A. Margo, "The Labor Force in the Nineteenth Century," in *The Cambridge Economic History of the United States,* ed. Stanley L. Engerman and Robert E. Gallman (Cambridge: Cambridge University Press, 2000), 2:209; U.S. Department of Commerce, *Historical Statistics of the United States: Colonial Times to 1970* (Washington, D.C.: Government Printing Office, 1975), D167–74.

14. Machinists were even more important in early-industrializing sectors. Inventors in other industries were not fundamentally different occupationally, however, from the six early sectors. If the six sectors were excluded from the all-inventor sample, machinists still would have been issued one-quarter of patents in the remainder of the economy.

15. Sokoloff and Khan, "Democratization of Invention," 369. My estimate of machinists as having received 29 percent of patents issued to inventors with known occupations is consistent. Employees in the machinery industry quadrupled from 1840 to 1860, roughly doubling their share of manufacturing workers, which could have accounted for machinists' growing patenting. Some in the sample did not work as machinists over the entire period of their invention, so their technological learning could have had other sources. Occupational shifts were common. City directories document that 11 machinists held other occupations at various points of their inventive careers, 4 in related occupations such as lock making and shipbuilding and 4 in scientific and inventive occupations. Still, in other occupations the proportion who shifted occupations was just as high, and some from this group became machinists.

16. The causality may have run in both ways. Principals may have learned and invented more, but invention also provided means to become principals. As chap. 5 will argue, both directions applied. Relatively few principals followed Edison's path of hiring workers to invent but then patenting solely in the employer's name. But machinery principals worked closely with their employees and doubtless learned from them and patented improvements to which employees contributed. In addition, employees may have invented but, with restricted income, not patented.

17. For a good study using these sources, see B. Zorina Khan and Kenneth L. Sokoloff, "'Schemes of Practical Utility': Entrepreneurship and Innovation among 'Great Inventors' in the United States, 1790–1865," *Journal of Economic History* 53 (June 1993): 289–307. They examine 160 inventors with major patents through 1846, with a focus on their market responsiveness and entrepreneurial character. I extend the set to a somewhat broader group and include major inventions through 1865. Many of the conclusions they reach concerning urbanization, education, and occupational and geographical mobility also apply to later inventors.

18. The group is doubtlessly arbitrary at the margins. Matthias Baldwin was listed as a manufacturer though his 19 patents through 1865 were important for his locomotive design. I included such cases. An uncorrectable bias stemmed from the focus on major, ascending industries at the expense of others. The important wood-planing inventor William Woodworth, for example, did not merit an entry. Fourteen patentees born between 1836 and 1845 were omitted because they typically were only beginning their inventive careers before the Civil War. Another 56 born through 1835 innovated but

did not receive patents, confirming that innovations were not fully reflected by patent statistics.

19. Of the 282 surveyed inventors with patents, 218 were classified as inventors. They averaged slightly more patents—7.4 versus 6.8—but mirrored all innovators in most characteristics. There were two significant differences; in the broader data set the shares of college-educated and of scientific occupations were higher, largely explained by the inclusion of engineers. Because of the similarities, the broader set will be used for the rest of the book.

20. Among innovators who did not receive patents, the share with scientific occupations was considerably higher, at 45 percent, largely because such innovators concentrated in engineering activities in construction and transportation, in which innovations were often not patented. Machinists constituted another 35 percent.

21. On the extent and content of college education, see Stanley M. Guralnick, "Sources of Misconception on the Role of Science in the Nineteenth-Century American College," in *Science in America since 1820,* ed. Nathan Reingold (New York: Science History Publications, 1976), 48–62. A few others attended college after completing their major inventions.

22. The actual number surely was higher because biographical entries often reported little about the mode of training. Some entries reported scientific activities (such as extensive experimentation) or knowledge (such as about alloys) or outcomes (such as developing the "science of lighting") but not how inventors learned. Such innovators were not included among mechanicians because they could have learned on the job. The term *mechanician* sometimes is limited to holders of mechanical knowledge, but I also include those with chemical, electrical, or civil knowledge.

23. Of eight prewar innovators in a broader study of nineteenth-century invention, five invented after the war, averaging 20 postbellum patents. Thomson, "Inventors and Technological Communication."

24. Because patentees with both urban and rural patents are classified as urban, the share of urban patents and urban repeat inventors is somewhat too high. But the bias is not great; most urban inventors received the large majority of their patents in urban areas. On the urban location of machinery workers, see David R. Meyer, *Networked Machinists: High-Technology Industries in Antebellum America* (Baltimore: Johns Hopkins Univ. Press, 2006).

25. Of course, the South's patent share was especially low during the Civil War, but its share of patents from 1836 through 1860 declined from its 1790–1835 share. The West's far larger share of inventors than machinery workers was partly due to its surge of patents in the late 1850s and early 1860s, when its share of machinery workers had grown.

26. Although Wallace was referring to machinery producers, the fraternity included many others. Anthony F. C. Wallace, *Rockdale: The Growth of an American Village in the Early Industrial Revolution* (New York: Knopf, 1978), 211; Eugene S. Ferguson, ed., *Early Engineering Reminiscences (1815–1840) of George Escol Sellers* (Washington, D.C.: Smithsonian Institution, 1965). Data on immigrants comes from various biographical dictionaries.

27. Sokoloff, "Inventive Activity in Early Industrial America."

28. On the other hand, occupations that made many products, such as carpenters, turners, and other woodworkers, spread patenting widely.

29. The low share of steam engineering users, here confined to boilermakers, plumbers, and boat makers, greatly understates the role of engine users, who included many occupations, including machinists.

30. Innovators without patents invented in areas largely mirroring those with patents. Inventors with scientific occupations concentrated on transportation, construction, and scientific innovations, machinists in metalworking and power innovations, and farmers in agricultural innovations. In comparison to all innovators, early-industrializing sectors had higher proportions of machinists and lower proportions of scientific or other manufacturing occupations.

31. I restricted the patentees examined to those who began inventing before 1861, so each inventor had at least four years to record post-patent assignments. Such patentees averaged more patents than those who first patented after 1860 because later inventors had less time to continue inventing. The occupational distribution of patentees researched for assignments closely matched the distribution of all patentees, with slightly lower shares of science, invention, and other manufacturers. On the market for patent rights later in the century, see Naomi R. Lamoreaux and Kenneth L. Sokoloff, "Inventors, Firms, and the Market for Technology in the Late Nineteenth and Early Twentieth Centuries," in *Learning by Doing in Markets, Firms, and Countries,* ed. Naomi Lamoreaux, Daniel M. G. Raff, and Peter Temin (Chicago: Univ. of Chicago Press, 1999), 19–57.

32. The actual share of patents assigned was higher because assignments before 1836 or in 1865 were not included and only a few assignments for each inventor were examined. In addition, assignment records typically did not list patent numbers but only a short description and perhaps a year of patenting. For inventors with many patents along the same line, patents were included only if there was positive evidence that they were assigned. Spencer Driggs had 19 assignments, and all surveyed were for musical instruments. Only 2 were clearly distinct, so although he had 7 pianoforte patents, 2 were included as assigned.

33. The importance of technological capabilities points to a limit of demand-led invention arguments. Some areas with access to markets but weak capabilities lagged greatly in invention, such as the South along the Mississippi and in New Orleans or Charleston. Access to knowledge—technological, production, financial, and marketing—was cheaper and easier to acquire for some occupations and locations, giving certain inventors advantages over others.

Chapter 5. Machinists as a Technological Center

1. "The Scientist, Inventor, and Mechanic," *Scientific American* 20, April 10, 1869, 233.

2. David R. Meyer offers the best overview of the role of machinists in networks in *Networked Machinists: High-Technology Industries in Antebellum America* (Baltimore: Johns Hopkins Univ. Press, 2006).

3. The classical statement about convergences in the machinery sector is Nathan Rosenberg, "Technological Change in the Machine Tool Industry, 1840–1910," *Perspectives on Technology* (Cambridge: Cambridge Univ. Press, 1976). See also Joseph W. Roe, *English and American Tool Builders* (New Haven, Conn.: Yale Univ. Press, 1916); David A. Hounshell, *From the American System to Mass Production, 1800–1932* (Baltimore: Johns Hopkins Univ. Press, 1984); Monte A. Calvert, *The Mechanical Engineer in America, 1830–1910* (Baltimore: John Hopkins Univ. Press, 1967). On the issue of ongoing technological change and the need for knowledge from outside the crafts, see Joel Mokyr, *The Gift of Athena: Historical Origins of the Knowledge Economy* (Princeton: Princeton Univ. Press, 2002).

4. Both of these underestimate the number of machinists to a greater extent than later censuses. Many firms were omitted. Neither Rhode Island nor Massachusetts reported machinery firms in 1820, though they were leaders in textile machinery, and the McLane Report includes no machinery firms from New York City and only one from Philadelphia. The state of New York, well represented in 1820 and 1840, provides a rough sense of growth; its 200 reported machinery workers in 1820 expanded to 3,600 by 1840. If New York's share was unchanged over these two decades, the nation would have had around 720 machinery employees in 1820. The case of Rhode Island indicates the hazards of relying on early surveys. The McLane Report listed 40 foundries and machine shops in 1831 employing 1,242 workers but did not distinguish between firms making textile machinery and casting stoves. The state reported only 534 machinery workers and 29 ironworkers in 1840. Clearly, something is amiss. The 1840 census also omitted important firms in other states, including Locks and Canals in Massachusetts.

5. Surveyed firms constituted two-fifths of the national total of machinery firms and related foundries and employed seven-tenths of the industry's workers. Large firms were overrepresented, and firms in the South and West were underrepresented. Machinery firms were essentially the same as machinery establishments because very few firms listed more than one establishment.

6. The average of 48.4 workers in surveyed firms was well above the 28.5 of all machinery firms. The difference resulted mostly from the counties surveyed, which in published data averaged 42.0 workers, but also because ancillary firms making horsepowers, cotton gins, sewing machine needles, and some textile machine parts were not surveyed.

7. Nathan Rosenberg, ed., *The American System of Manufactures* (Edinburgh: Edinburgh Univ. Press, 1969), 331.

8. Why some sectors specialized is an interesting question. Sewing machine and agricultural machinery firms both made new, standardized products for wide, relatively homogeneous markets; they grew by specializing in one type of product. Textile machinery firms produced to the custom order of a much smaller number of mill owners mostly in small New England towns. The complex design and production requirements of textile machines and the one-industry character of many machine-producing towns may have narrowed communication networks. Nevertheless, some notable firms, including William Mason, Lowell Machine Shop, and Amoskeag, did diversify.

9. Only counties surveyed in both censuses were included, which restricts coverage to Mid-Atlantic States, New England, and a few counties in Ohio. Focusing on the more settled East underestimates the multiplication of firms because so many western firms were new. Categorizing firms by machinery type is occasionally difficult. Merrick & Sons, for example, a prominent Philadelphia producer of sugar mill equipment, steam engines, and gasworks, was categorized with milling equipment in 1850 but was put among generic firms in 1860 because it listed its products but not their values. In cases such as this one, in which the product mix remained the same, firms were recategorized to achieve consistency between years. A small part of the shifts in numbers of firms among machinery types reflected easier categorization of specialties in 1860.

10. Among counties surveyed in 1850 and 1860, fewer than 30 percent of machinery firms in 1850 are known to have persisted as machinery firms until 1860. Although there surely are other reasons for this discontinuity—changing firm names and illegible records are only two—many firms simply went under. If half of U.S. machinery firms persisted in some form over the decade, then, given the growth in the number of firms, 70 percent of the machinery firms in 1860 originated during the decade.

11. Considerable investment was required to train workers, mostly in terms of wages and the labor time of supervisors or workers undertaking the training, and firms had an incentive to avoid training costs by hiring workers trained by others. Why were firms willing to incur these costs when workers could readily leave the firm? Apprenticeship fees defrayed these costs for some workers, but formal apprenticeship was declining. Corliss promised presents to two workers if they stayed until they were twenty-one. George H. Corliss, "Memoranda Books," Papers, 1835–1962 (Brown University, John Hay Library, Providence, R.I.). Many firms limited early training to simple mechanical operations separated from design functions, but machinists needed some design skills to complete their jobs, which increased their value to others. Firms with strong reputations attracted high-quality workers and trainees and could recoup training costs in higher prices. Where workers were mobile among local machinery firms, external economies and norms of training could benefit all firms, such as they did in the armory system organized by the Ordnance Department. Merritt Roe Smith, *Harpers Ferry Armory and the New Technology* (Ithaca, N.Y.: Cornell Univ. Press, 1977).

12. Robert Willis, "Machines and Tools for Working in Metal, Wood, and Other Materials," *Lectures on the Results of the Great Exhibition of 1851* (London: David Bogue, 1852), 300.

13. Hoe's letterbooks include extended discussions about these contracts through the mid-1840s. Richard M. Hoe and Company, "Letterpress Book, 1834–1858," Records, 1824–1953 (New York: Columbia University); Hoe MSS; Frank E. Comparato, *Chronicles of Genius and Folly: R. Hoe & Company and the Printing Press as a Service to Democracy* (Culver City, Calif.: Labyrinthos, 1979), 129–36.

14. J. Leander Bishop, *A History of American Manufactures from 1608 to 1860* (Philadelphia: E. Young, 1868), 3:302.

15. One reason machinists were so inventive was that the occupation attracted the

mechanically adept. Histories of well-known machinists commonly point to childhood technological interests and accomplishments. Even if so, training as machinists itself directed their learning and invention, and the lower inventiveness of machinists outside cities and in the South suggests that more was at work than mere aptitude. If the machinery sector was a particularly strong attractor of mechanical talent, this may itself attest to its particular role in ongoing technological change.

16. Patent assignment could combine with production in the inventor's own firm, such as when inventors assigned patents in some geographical areas and produced in others. According to assignment records, Cyrus McCormick did just this when he sold his reaper patent rights in Monroe and Orleans counties in New York but nowhere else.

17. Many other directories were consulted but did not list persisting machinists. Machinery firms were typically partnerships holding the name of the partners or the leading partner. The first partner was included in the sample if the full name could be identified, except if the firm was known to have retained the name of a dead principal. When two partners persisted over time, both were investigated. The procedure is biased against firms with generic names, including large corporations, which are represented by their superintendents. Firms from the Mid-Atlantic and New England states formed 79 percent of the sample, above their 64 percent of machinery firms. The South and West were underrepresented due to their lower urbanization, lack of business directories, and undersampling in census manuscripts. The Steam Engine Report was biased toward engine-making and engine-using firms, but relatively few firms were identified from this source, and the firms were also identified from another source.

18. Investigated principals included many leading inventors, including William Mason, Charles Danforth, George Corliss, Richard Hoe, Matthias Baldwin, William Sellers, Joseph Brown, Cyrus McCormick, Isaac Singer, and Allen Wilson. Some important machinist-inventors were excluded because they did not manufacture (including Elias Howe in sewing machines) or invented to make other products (such as Elisha Root in firearms).

19. Bishop, *History,* 3:302–3.

20. The patenting behavior of these sectors depended more on specialization than on the length of production runs. Of firms surveyed in the census manuscripts, the average output was 24 for locomotive firms (led by the 90 of the Rogers Locomotive Works), 20 for printing presses (led by Hoe's 140), 495 for reapers and mowers (led by McCormick's 4,100), and 2,983 for sewing machines (led by Wheeler and Wilson's 37,100, with 17 companies making at least 500). That agricultural and sewing machinery firms mass-produced did not differentiate their patenting behavior from locomotives or printing presses. By contrast steam engine firms had production runs about the same as locomotives and printing presses but quite different patenting behavior.

21. Given the disproportionate share of evidence about urban machinists, this share overstates their actual proportion in the economy, but these cities did employ 22 percent of the nation's machinery workers.

22. Territorial assignments were common for sewing machines, agricultural ma-

chinery, and woodworking machinery. The best case studies are for woodworking; see Carolyn C. Cooper, *Shaping Invention: Thomas Blanchard's Machinery and Patent Management in Nineteenth-Century America* (New York: Columbia Univ. Press, 1991); and Carolyn C. Cooper, "A Patent Transformation: Woodworking Mechanization in Philadelphia, 1830–1856," in *Early American Technology: Making and Doing Things from the Colonial Era to 1850*, ed. Judith A. McGaw (Chapel Hill: Univ. of North Carolina Press, 1994), 278–327.

23. The difference in patenting rates would have been considerably larger if firms were included that did not persist for four years. A larger share of firms developed new techniques; some did not patent in principals' names but used inventions that were unpatented, patented by nonprincipals, or assigned.

24. Persisting firms with patents grew somewhat more rapidly in employment than firms without patents (50 to 43%) and in the value of output (97 to 90%). Patenting firms were only slightly larger in 1850, suggesting few economies of scale in innovation. Among such firms, however, those surviving until 1860 had been somewhat larger in 1850 than firms failing over the 1850s (74 to 56 workers), so that size may have brought some advantages. Size and patenting were unlinked among established industries, reflecting the role of large engine-making firms in which principals did not invent. But in sectors making new types of machinery, firms with patents were larger.

25. On Allen's experience, see Zachariah Allen, Papers, 1767–1946, "Autobiography," MS (Rhode Island Historical Society, Providence). On limits to machine making, see Comparato, *Chronicles of Genius and Folly*; Louis C. Hunter, *A History of Industrial Power in the United States, 1780–1930*, vol. 2: *Steam Power* (Charlottesville: Univ. Press of Virginia, 1985), 197–223.

26. Rosenberg, "Technological Change in the Machine Tool Industry," 9–31.

27. Machinists learned more widely. A surprisingly large number of machinists had substantial exposure to systematic learning off the job, including over one-third of 119 prominent machinists listed in biographical dictionaries. Only a few had college education, but many others studied widely, read the *Scientific American* and technology books that libraries increasingly stocked, or participated in mechanics' institutes, including Matthias Baldwin and William Sellers in the Franklin Institute. Bruce Sinclair, *Philadelphia's Philosopher Mechanics: A History of the Franklin Institute, 1824–1865* (Baltimore: Johns Hopkins Univ. Press, 1974).

28. As the records of Betts & Seal and the Providence Iron Foundry indicate, production convergence in foundries began before the 1830s. Cross-industry technologies emerged incrementally, preparing the way for the 1830s when cross-fertilization became more common and important. Betts & Seal, Records, 1828–67 (Hagley Museum and Library, Wilmington, Del.); Providence Iron Foundry, "Ledgers, 1817–1832" and "Order Books, 1826–1832" (Slater Collection. Baker Library, Harvard Business School, Boston); William Sellers & Co., "Order Book," 1848–54 (Hagley Museum and Library, Wilmington, Del.).

29. William Sellers & Co., "Order Book."

30. Gene Silvero Cesari, "American Arms-Making Machine Tool Development,

1798–1855" (Ph.D. diss., University of Pennsylvania, 1970); Smith, *Harpers Ferry Armory,* 287–90.

31. David J. Jeremy, *Transatlantic Industrial Revolution: The Diffusion of Textile Technologies between Britain and America, 1790–1830s* (Cambridge, Mass.: MIT Press, 1981), 111; Roe, *English and American Tool Builders;* Smith, *Harpers Ferry Armory.* Maudslay is not known to have sold any industrial lathes, though he did sell slide lathes to gentlemen hobbyists (which led one contemporary book to treat the slide lathe as an ingenious curiosity). K. R. Gilbert, *Henry Maudslay: Machine Builder* (London: HMSO, 1971), 28; J. Holland, *A Treatise on the Progressive Improvement and Present State of the Manufactures in Metal* (London: Longman, 1831), 1:136–37.

32. "A Description of the American Slide Rest, as Made by Messrs. Mason & Tyler, of Philadelphia, with the Improvements of Other Machinists," *Journal of the Franklin Institute* 2 (1826): 104–5; Eugene S. Ferguson, ed. *Early Engineering Reminiscences (1815–1840) of George Escol Sellers* (Washington, D.C.: Smithsonian Institution, 1965), 44, 54, 88, 112. Sellers visited Maudslay's shop in 1832 and felt that Philadelphia lathes of several years earlier were superior. The breadth of functions emerges from an 1830 Philadelphia city directory ad describing the firm of John Kinnan, a "machinist and turner in iron, brass, ivory, hard wood, etc."

> MANUFACTURES TURNING LATHES of various kinds, Slide Lathes and Slide Rests, Screw Plates, Taps and Dies; Taps and Boxes for Wood Screws; Hose Screws and Engine work; patent, and plain Carriage and Gig Axles; Die and Punch Turning; Silversmith's and Jewellers Plating Mills made and repaired; Experimental Machinery, Cutler's turning; Printing Press Makers turning; Silversmith's and Jewellers turning; Turning and Screw Tools of all descriptions, Turning, filing, drilling, screwing, and fitting up of any kind of work; Founders' iron or wooden patterns made.

Kinnan sold both lathes and parts made on lathes, and the range of industries listed—engines, carriages, silver, printing presses and, later in the ad, cabinets, leather, and a variety of ivory work—demonstrated the universality of lathe work. *Desilver's Philadelphia Directory and Stranger's Guide, 1830* (Philadelphia: Robert Desilver, 1830), n.p.

33. Andrew Campbell tried but could find no engine lathe around Columbia., Mo. in 1847. Andrew Campbell, "Autobiography," Papers, 1840–1926 (Wilmington, Del.: Hagley Museum and Library).

34. William Sellers, "Machinery Manufacturing Interests," in *1795–1895: One Hundred Years of American Commerce,* ed. Chauncey M. Depew, 2 vols. (New York: D. O. Haynes, 1895), 348.

35. Roe, *English and American Tool Builders,* 50–53, 247–54; Locks and Canals, "Letter Books," DA1-6 (Baker Library, Harvard Business School); Comparato, *Chronicles of Genius and Folly,* 154–59; Hoe, "Letterpress book, 1834–1858"; Sellers, "Order Book," 1848; Bishop, *History.*

36. Brown & Sharpe, *A Brown and Sharpe Catalogue Collection* (Mendham, N. J.: Astragal, 1997), 24–30.

37. U.S. patents 10,491; 20,446; and 27,478, respectively.

38. U.S. patent 4,548.

39. Hunter, *Steam Power.* Corliss's competitors recognized that his manufacturing methods rivaled his engine design as a source of his success.

40. On Ames, see Smith, *Harpers Ferry Armory,* 287–90. On Committee on Machinery purchases, see Rosenberg, *American System of Manufactures,* 180–92. Sellers's Philadelphia rival, Bement & Dougherty, also made machine tools. Its total output of $198,000 was slightly smaller, but its machine tool output was unstated.

41. Steven Klepper and Sally Sleeper, "Entry by Spinoffs," MS, 2000.

42. *The Wilmington Directory, 1857,* comp. William H. Boyd (Wilmington, Del.: William H. Boyd, 1857), n.p.

43. On barriers to production in the absence of lathes and planers and the complementarity of changes in the two, see Comparato, *Chronicles;* Hunter, *Steam Power,* 197–223.

44. The government played an important role in spreading machine tools. It let many firearms contracts to firms outside the firearms industry and required knowledge sharing among contractors. Brown & Sharpe built machinery for many of them, including the universal miller, turret lathes, and other milling machines. See *Brown and Sharpe Catalogue Collection* for a description of these machines and their users.

45. John K. Brown, "When Machines Became Gray and Drawings Black and White: William Sellers and the Rationalization of Mechanical Engineering," *IA: Journal of the Society for Industrial Archeology* 25 (1999): 29–54.

46. *Brown and Sharpe Catalogue Collection,* 22; Hounshell, *From the American System to Mass Production;* Grace Rogers Cooper, *The Invention of the Sewing Machine* (Washington, D.C.: Smithsonian Institution, 1968); Ross Thomson, *The Path to Mechanized Shoe Production in the United States* (Chapel Hill: Univ. of North Carolina Press, 1989).

47. As chapter 4 documented, machinists were an important minority among major innovators; they commercialized inventions coming from many industries. See also B. Zorina Khan and Kenneth L. Sokoloff, "'Schemes of Practical Utility': Entrepreneurship and Innovation among 'Great Inventors' in the United States, 1790–1865," *Journal of Economic History* 53 (June 1993): 289–307.

48. Thomas W. Harvey, Harvey Family Papers, 1796–1913 (Hagley Museum and Library, Wilmington, Del.); Thomson, *Path to Mechanized Shoe Production.*

49. Perhaps most important, industries could locate in urban areas, which, given stronger urban inventiveness, supported ongoing invention. Nathan Rosenberg and Manuel Trajtenberg, "A General-Purpose Technology at Work: The Corliss Steam Engine in the Late Nineteenth-Century United States," *Journal of Economic History* 64 (March 2004): 61–99.

50. *Trow's New York City Directory, compiled by H. Wilson, for the Year Ending May 1, 1861* (New York: John F. Trow, 1860), opposite 929.

Chapter 6. Science, Mechanicians, and Invention

1. *Capital: A Critique of Political Economy* (London: Vintage, 1976), 1:616–17.

2. Eugene S. Ferguson, ed., *Early Engineering Reminiscences (1815–40) of George Es-*

col Sellers (Washington, D.C.: Smithsonian Institution, 1965), 16. This account is taken largely from Sellers's reminiscences, supplemented by Greville Bathe and Dorothy Bathe, *Jacob Perkins: His Inventions, His Times and His Contemporaries* (Philadelphia: Historical Society of Pennsylvania, 1943); and various entries in the *Dictionary of American Biography.*

3. Ferguson, *Early Engineering Reminiscences,* 21.

4. Joel Mokyr, *The Gift of Athena: Historical Origins of the Knowledge Economy* (Princeton: Princeton Univ. Press, 2002), 4–6.

5. Mokyr, *Gift of Athena,* 7–8, 33–77.

6. Alexis de Tocqueville, *Democracy in America* (New York: Vintage, 1945), 2: 42–43.

7. George H. Daniels, *Science in American Society* (New York: Knopf, 1971); George H. Daniels, "The Process of Professionalization in American Science: The Emergent Period," in *Science in America since 1820,* ed. Nathan Reingold (New York: Science History Publications, 1976), 48–62; Nathan Reingold, *Science, American Style* (New Brunswick, N.J.: Rutgers Univ. Press, 1991); Donald deB. Beaver, *The American Scientific Community, 1800–60* (New York: Arno, 1980); Stanley M. Guralnick, *Science and the Ante-bellum College* (Philadelphia: American Philosophical Society, 1975); Stanley M. Guralnick, "Sources of Misconception on the Role of Science in the Nineteenth-Century American College," in *Science in America since 1820,* ed. Nathan Reingold (New York: Science History Publications, 1976), 48–62; Robert V. Bruce, *The Launching of Modern American Science, 1846–76* (Ithaca, N.Y.: Cornell Univ. Press, 1987).

8. Edwin T. Layton Jr., "Mirror-Image Twins: The Communities of Science and Technology," in *Nineteenth-Century American Science: A Reappraisal,* ed. George H. Daniels (Evanston, Ill.: Northwestern Univ. Press, 1972), 210–30.

9. Daniel R. Headrick, *When Information Came of Age: Technologies of Knowledge in the Age of Reason and Revolution, 1700–1850* (Oxford: Oxford Univ. Press, 2000); John Nicholson, *The Operative Mechanic, and British Machinist* (Philadelphia: H. C. Carey & I. Lea, 1826).

10. Eugene S. Ferguson, *Oliver Evans: Inventive Genius of the American Industrial Revolution* (Greenville, Del.: Hagley Museum, 1980), 28–32, 42–44.

11. Ferguson, *Early Engineering Reminiscences,* 40.

12. Edward W. Stevens Jr., *The Grammar of the Machine: Technical Literacy and Early Industrial Expansion in the United States* (New Haven, Conn.: Yale Univ. Press, 1995), 41–45; Zachariah Allen, *The Science of Mechanics* (Providence, R.I.: Hutchins & Cory, 1829); Jacob Bigelow, *Elements of Technology* (Boston: Hilliard, Gray, Little & Wilkins, 1831); *Appleton's Dictionary of Machines, Mechanics, Engine-work, and Engineering* (New York: D. Appleton, 1851); Layton, "Mirror-Image Twins," 216–20. In addition to general texts, industry-specific works on bridges and railroads found audiences. For a study of the geometry of railroad engineering, complete with logarithms, see John B. Henck, *Field-book for Railroad Engineers* (New York: D. Appleton, 1854).

13. "Address," *Journal of the Franklin Institute* 1 (January 1826): 2.

14. The journal was a locus of dispute between those who targeted the masses of craftsmen and those oriented more to scientists. Over the course of the 1830s, under

the leadership of Alexander Bache, the balance tilted toward sciences, before shifting back toward industrial interests. Bruce Sinclair, *Philadelphia's Philosopher Mechanics: A History of the Franklin Institute, 1824–1865* (Baltimore: Johns Hopkins Univ. Press, 1974), 195–216.

15. Michael Borut, "The *Scientific American* in Nineteenth Century America" (Ph.D. diss., New York Univ., 1977), 65–69.

16. Jones could be scathing, such as his review of a boat-propelling mechanism: "We may safely aver, however, that in the multitude of devices which have entered into the heads of schemers, with and without brains, there is no one less feasible than this." *Journal of the Franklin Institute* 6 (June 1830): 4.

17. Daniel Hovey Calhoun, *The American Civil Engineer: Origins and Conflict* (Cambridge, Mass: Technology Press, MIT, 1960); Terry Mark Aldrich, *Rates of Return on Investment in Technical Education in the Ante-bellum American Economy* (New York: Arno Press, 1975).

18. The institute tried to direct invention by offering medals and cash awards. In 1826 it offered 61 silver medals for cast steel, iron pipes, machinery castings, scales, screws, and other mechanisms. "List of Premiums Offered by the Franklin Institute of the State of Pennsylvania, and to Be Awarded at Their Third Annual Exhibition, in 1826," *Journal of the Franklin Institute* 1 (January 1826): 6–10. Later it advertised cash awards for locomotive spark arrestors, anthracite-burning stoves, rolled iron, and street lamps. Awards were often funded by firms and, in the case of lamps, by the city of Philadelphia. Whether such awards succeeded at directing invention is unclear, but exhibitors did gain sales, and award winners often advertised their victories. Sinclair, *Philadelphia's Philosopher Mechanics,* 93–103.

19. Sinclair, *Philadelphia's Philosopher Mechanics.*

20. Daniel Headrick's *When Information Came of Age* nicely described these information-storing and spreading systems, with a particular focus on Europe.

21. Guralnick, *Science and the Ante-bellum College.*

22. Eugene S. Ferguson, *Kinematics of Mechanisms from the Time of Watt. Contributions from the Museum of History and Technology,* bulletin 228, paper 27 (Washington, D.C.: Smithsonian Institution, 1962); Layton, "Mirror-Image Twins."

23. Stevens, *Grammar of the Machine,* 2.

24. Nicholson, *Operative Mechanic,* v.

25. Sinclair, *Philadelphia's Philosopher Mechanics,* 197.

26. Joseph Henry, *The Papers of Joseph Henry,* ed. Nathan Reingold (Washington, D.C.: Smithsonian Institution, 1972), 1:384.

27. Quoted in "Dignity of Patents," *American Polytechnic Journal* 1 (January–June 1853): 28.

28. Quoted in "Dignity of Patents," 28.; Robert C. Post, "The Page Locomotive: Federal Sponsorship of Invention in Mid-19th Century America," *Technology and Culture* 13 (April 1972): 140–69.

29. See Beaver, *American Scientific Community,* for a list of contributors. Scientists did play other roles. They communicated with prospective inventors. While Joseph Henry complained of the ignorance of perpetual motion inventors who contacted

him, many communications were more productive. Evans had useful interactions about his steam engine with Robert Patterson, a University of Pennsylvania mathematics professor (and a visitor to Perkins's shop). Francis Lowell called on a Harvard mathematics professor to examine Aza Arnold's differential gear.

30. Paul Israel, *From Machine Shop to Industrial Laboratory: Telegraphy and the Changing Context of American Invention, 1830–1920* (Baltimore: Johns Hopkins Univ. Press, 1992); Brooke Hindle, *Emulation and Invention* (New York: NYU Press, 1981); David P. Billington, *The Innovators: The Engineering Pioneers Who Made America Modern* (New York: John Wiley & Sons, 1996).

31. "Jacob Cist," "George Mordley Mowbray," "Samuel Wetherill," and "Benjamin Silliman," in *Dictionary of American Biography.* On the chemical industry, see William Haynes, *American Chemical Industry: Background and Beginnings* (New York: D. Van Nostrand, 1954), vol. 1.

32. Merritt Roe Smith, "Army Ordnance and the 'American System' of Manufacturing, 1815–1861," in *Military Enterprise and Technological Change,* ed. Merritt Roe Smith (Cambridge, Mass.: MIT Press, 1985), 70–75; Harold F. Williamson and Arnold R. Daum, *The American Petroleum Industry: The Age of Illumination, 1859–1899* (Evanston, Ill.: Northwestern Univ. Press, 1959), 63–112.

33. Calhoun, *American Civil Engineer;* Monte A. Calvert, *The Mechanical Engineer in America: 1830–1910* (Baltimore: John Hopkins Univ. Press, 1967).

34. Calhoun, *American Civil Engineer,* 25–53; Aldrich, *Rates of Return on Investment in Technical Education.* On the variety of paths and outcomes of engineering training, see Merritt Roe Smith, "Becoming Engineers in Early Industrial America," Program in Science, Technology, and Society pamphlet no. 13 (Cambridge: Massachusetts Institute of Technology, 1990).

35. F. Daniel Larkin, *John B. Jervis: An American Engineering Pioneer* (Ames: Iowa State Univ. Press, 1990).

36. At the time those who ran steam engines on boats or in mills often were called engineers. I exclude them from my measures, categorizing them instead as machinists.

37. Billington, *Innovators,* 48.

38. Many engineering innovators did not have patents, including 21 in the major innovators sample. They had similar innovative objects as those with patents, concentrating on construction and transportation projects.

39. Edwin. T. Layton Jr., "James B. Francis and the Rise of Scientific Technology," in *Technology in America,* ed. Carroll W. Pursell Jr. (Cambridge, Mass.: MIT Press, 1990); Edwin T. Layton Jr., "Millwrights and Engineers: Science, Social Roles, and the Evolution of the Turbine in America," in *The Dynamics of Science and Technology,* ed. Wolfgang Krohn, Edwin T. Layton Jr., and Peter Weingart (Dordrecht, Holland: D. Reidel, 1978); Louis C. Hunter, *A History of Industrial Power in the United States, 1780–1930,* vol. 1: *Waterpower in the Century of the Steam Engine* (Charlottesville,: Univ. Press of Virginia, 1979); James B. Francis, *Lowell Hydraulic Experiments* (New York: Van Nostrand, 1871).

40. *Wood's Baltimore City Directory* (Baltimore: John W. Woods, 1860), 9 (advertisements); see also Emory L. Kemp, ed., *American Bridge Patents: The First Century, 1790–1890* (Morgantown,: West Virginia Univ. Press, 2005).

41. Most West Point graduates through 1840 did not work as engineers, though they often innovated in other spheres. That a Military Academy education was expensive and that so small a share of its graduates used their expertise for the government, and these often not for long, led one scholar to argue that the social rate of return on investment in the college was relatively meager (Aldrich, *Rates of Return on Investment in Technical Education)*. Yet many graduates undertook private innovations, which added to the social returns of their education.

42. Interestingly, the three most prolific engineer-patentees administered transportation improvements, not merely designing them, Sullivan in canal and water delivery companies, Long as a railroad engineer, and John Stevens as a steamboat pioneer and rival of Fulton. They took out almost half of the 57 patents issued to engineer-inventors.

43. *Mechanical Engineers in America Born prior to 1861: A Biographical Dictionary* (New York: American Society of Mechanical Engineers, 1980), vii. The enormous breadth of mechanical engineers is indicated by the listings in engineering societies' biographical dictionaries. Among 32 listed civil engineers who qualified as major innovators, two-thirds were employed principally as engineers, and three-quarters innovated in construction and transportation. By contrast, listed mechanical engineers constituted over half of all major innovators, two-thirds with machinery and other mechanical occupations, and their innovations mirrored the distribution for all innovators, if a bit lower in construction and science.

44. Charles W. Copeland advertisement, *Scientific American,* January 3, 1852.

45. *Trow's New York City Directory, Compiled by H. Wilson, for the Year Ending May 1, 1861* (New York: John F. Trow, 1860), business directory, 133. Copeland and Richards both mentioned drafting services. On the connection of drafting to mechanical engineering, see John K. Brown, "When Machines Became Gray and Drawings Black and White: William Sellers and the Rationalization of Mechanical Engineering," *IA: Journal of the Society for Industrial Archeology* 25 (1999): 29–54.

46. "Artisan," *Journal of the Franklin Institute* 2 (1826): 353.

47. As noted earlier, others systematically experimented but were not classified as mechanicians because biographies do not reveal whether this capability came from outside their occupation or within it.

48. The assessment of Shaw's invention was published in "Remarks by the Editor" to "observations and inquiries respecting the material employed in the fabrication of Detonating Powder. By Joshua Shaw, Esq.," *Journal of the Franklin Institute,* n.s. 6 (1830): 108–10.

49. Sinclair, *Philadelphia's Philosopher Mechanics,* 15–18.

50. Zachariah Allen, "Autobiography," n.d., Papers, 1767–1946 (Rhode Island Historical Society, Providence).

51. Sinclair, *Philadelphia's Philosopher Mechanics,* 140–49, 170–94; *Journal of the Franklin Institute,* various issues.

52. Ferguson, *Early Engineering Reminiscences,* 15, 70; *Dictionary of American Biography;* Sinclair, *Philadelphia's Philosopher Mechanics*; *Journal of the Franklin Institute.*

53. John W. Lozier, *Taunton and Mason: Cotton Machinery and Locomotive Man-*

ufacture in Taunton, Massachusetts, 1811–1861 (New York: Garland, 1986); David A. Hounshell, *From the American System to Mass Production, 1800–1932* (Baltimore: Johns Hopkins Univ. Press, 1984); John Nader, "The Rise of an Inventive Profession: Learning Effects in the Midwestern Harvester Industry, 1850–1890," *Journal of Economic History* 52 (June 1994): 397–408.

54. Ross Thomson, *The Path to Mechanized Shoe Production in the United States* (Chapel Hill: Univ. of North Carolina Press, 1989).

55. Layton, "James B. Francis and the Rise of Scientific Technology" and "Millwrights and Engineers."

Chapter 7. The Patent System and the Inventive Community

1. Eugene S. Ferguson, ed., *Early Engineering Reminiscences (1815–1840) of George Escol Sellers* (Washington, D.C.: Smithsonian Institution, 1965), 38.

2. Evans did not point to government's classification or expert patent examination functions, but he did support an even stronger governmental role: "If government would, at the expense of the community, employ ingenious persons, in every art and science, to make with care every experiment that might possibly lead to the extension of our knowledge of principles, carefully recording the experiments and results so that they might be fully relied on, and leaving readers to draw their own inferences, the money would be well-expended." The government would not only record knowledge but also create it. Quoted in Eugene S. Ferguson, *Oliver Evans: Inventive Genius of the American Industrial Revolution* (Greenville, Del.: Hagley Library and Museum, 1980), 60–61.

3. The patent act of 1790, major successors in 1793 and 1836, and other minor changes contained many subtle differences and ambiguities that occasioned interpretation in the Patent Office and the courts. For these differences, see P. J. Federico, "Outline of the History of the United States Patent Office," *Journal of the Patent Office Society* (July 1936); Edward C. Walterscheid, *To Promote the Progress of Useful Arts: American Patent Law and Administration, 1798–1836* (Littleton, Col.: Fred B. Rothman, 1998); B. Zorina Khan, *The Democratization of Invention: Patents and Copyrights in American Economic Development, 1790–1920* (Cambridge: Cambridge Univ. Press, 2005), 49–65.

4. Walterscheid, *To Promote the Progress of Useful Arts,* 281–304; Bruce Sinclair, *Philadelphia's Philosopher Mechanics: A History of the Franklin Institute, 1824–1865* (Baltimore: Johns Hopkins Univ. Press, 1974), 42–45. On the British patent system, see H. I. Dutton, *The Patent System and Inventive Activity during the Industrial Revolution, 1750–1852* (Manchester: Manchester Univ. Press, 1984).

5. Walterscheid, *To Promote the Progress of Useful Arts,* 421–32; Federico, "Outline of the History," 91–102; Robert C. Post, *Physics, Patents, and Politics: A Biography of Charles Grafton Page* (New York: Science History Publications, 1976), 48–50. Several Patent Office workers helped frame the legislation, including Henry Ellsworth, its superintendent from 1835, Charles Keller, who maintained models, and the one-time superintendent Thomas Jones, who, when describing inventions in the *Journal of the Franklin Institute,* referred to the specification of claims in the same way that the act would.

6. Even the oath could propose problems, such as in the case of patent applications made by slaves noted in the 1857 *Annual Report of the Commissioner of Patents:* "As these persons could not take the oath required by statute, and were legally incompetent alike to receive a patent and to transfer their interest to others, the applications were necessarily rejected" (9). What might seem like a technical requirement involved nothing less than the legal recognition of the individual and would take a fundamental change in social relations to achieve.

7. Quoted in Post, *Physics, Patents, and Politics,* 51.

8. Post, *Physics, Patents, and Politics,* 118.

9. On the background of patent examiners and their relation to the broader scientific community, see Post, *Physics, Patents, and Politics,* 50–59.

10. Patent case files, available in the National Archives, include the original specification, correspondence with the applicant, and final specification for each patent.

11. *The Washington Directory, and Congressional, and Executive Register for 1850* (Washington, D.C.: Edward Waite, 1850), 197.

12. Patents agents existed informally before 1836 because most of their functions had importance under a registration system. Britain had a well-developed system of patent agents at the time, born around 1820, under a registration system. Dutton, *Patent System,* 86–102. The growth in patent applications in the 1840s and the need to draw up specifications meeting Patent Office standards help explain the origin (or at least formalization) of this profession.

13. Post, *Physics, Patents, and Politics,* 2–53; Patent Office files.

14. *Annual Report of the Commissioner of Patents,* 1850, 310 (hereafter *ARCP).*

15. *Washington Directory, 1850,* 196; *The Washington and Georgetown Directory* (Washington, D.C.: Alfred Hunter, 1853), 115; *Boston Directory, for 1855* (Boston: George Adams, 1855), advertisements, 7.

16. On the Scientific American Patent Agency, see "Patent Agency," *Scientific American* 5, September 22, 1849, 7; "Important to Inventors," *Scientific American* 12 (1857): 231, 319; and Michael Borut, "The *Scientific American* in Nineteenth Century America" (Ph.D. Dis.: New York University, 1977). On agencies and publications, see Post, *Physics, Patents, and Politics.*

17. On the development of drafting, see John K. Brown, "When Machines Became Gray and Drawings Black and White: William Sellers and the Rationalization of Mechanical Engineering," *IA: Journal of the Society for Industrial Archeology* 25 (1999): 29–54; and "Design Plans, Working Drawings, National Styles: Engineering Practices in Great Britain and the United States, 1775–1945," *Technology and Culture* 41 (April 2000): 195–238.

18. *The Boston Directory, 1861* (Boston: Adams, Sampson & Co., 1861), 62, advertising department. Making models and patterns overlapped; see F. W. Barrows, *Practical Pattern-Making* (New York: Norman W. Henley, 1906).

19. U.S. Patent Office, "Patent Assignment Digest" (National Archives, College Park, Md.), H1:87.

20. "On the Patentability and the Patenting of Inventions," *Scientific American*, 10 (1854–55):117.

21. Khan, *Democratization of Invention,* 66–105.

22. Patent agents were identified from city business directories and from Post, *Physics, Patents, and Politics.* Patent Office personnel were listed in Robert C. Post, "'Liberalizers' versus 'Scientific Men' in the Antebellum Patent Office," *Technology and Culture* 17 (January 1976): 24–54; *Annual Report of the Commissioner of Patents;* and particularly in city directories, including *The Washington Directory, and Governmental Register, for 1843* (Washington, D.C.: Anthony Reintzel, 1843), 118–19; *The Washington Directory, and National Register, for 1846* (Washington, D.C.: Gaither & Addison, 1846), 25; *The Washington Directory, and Congressional, and Executive Register for 1850* (Washington, D.C.: Edward Waite, 1850), 117; *Washington and Georgetown Directory,* 1853, 40.

23. Post, *Physics, Patents, and Politics.*

24. For officers and jurors, see Horace Greeley, *Art and Industry as Represented in the Exhibition at the Crystal Palace, New York, 1853–4* (New York: Redfield, 1853), xv–xviii. Occupations were determined from 1850 census manuscripts and the *Dictionary of American Biography.* Pure scientists were active participants; Benjamin Silliman was a juror assessing minerals, Alexander Bache assessed machines, and Joseph Henry and James Renwick judged philosophical instruments. There was considerable continuity among judges; Renwick and 10 other judges at the 1852 American Institute fair repeated in the New York Exhibition the following year. *Transactions of the American Institute of the City of New York for the Year 1852* (Albany, N.Y.: Charles Van Benthuysen), 17–110.

25. On the patent system in the late nineteenth century, see Naomi R. Lamoreaux and Kenneth L. Sokoloff, "Inventors, Firms, and the Market for Technology in the Late Nineteenth and Early Twentieth Centuries," in *Learning by Doing in Markets, Firms, and Countries,* ed. Naomi Lamoreaux, Daniel M. G. Raff and Peter Temin (Chicago: Univ. of Chicago Press, 1999), 19–57.

26. Although the prospect of patent rights provided an incentive to the inventor, patent rights held by others might discourage invention that could infringe on others' rights. The difficulty of judging the effects of the patent system is suggested by this tension: one's own patent rights can increase incentives to invent, but others' rights may reduce incentives. The issue is complicated by the encouragement that others' rights provide for attempts to find alternative solutions and by learning by studying patents, both of which might be socially beneficial.

27. Ferguson, *Oliver Evans,* 52.

28. David Wilkinson, "Reminiscences," in *The New England Mill Village, 1790–1860,* ed. Gary Kulik, Roger Parks, and Theodore Z. Penn (Cambridge, Mass.: MIT Press, 1982), 88.

29. B. Zorina Khan, "Property Rights and Patent Litigation in Early Nineteenth-Century America," *Journal of Economic History* 55 (March 1995): 58–97. One might wonder whether the small share of patents litigated means that patents offered little protection from infringement, especially when much litigation concerned rival inventors' claims and not direct infringement by users. Widely available patent descriptions might have made infringement easier. Yet many cases were not brought to court

because potential litigants could anticipate the outcome. Further, patentees would litigate cases in which monetary stakes were higher, which were relatively few. That so many assignees purchased patent rights suggests that legal channels significantly deterred infringement.

30. Lamoreaux and Sokoloff, "Inventors, Firms, and the Market for Technology." Ashish Arora earlier used a variant of the term in analyzing contemporary technological change in "Licensing Tacit Knowledge: Intellectual Property Rights and the Market for Know-how," *Economics of Innovation and New Technology* 4 (1995): 41–59. He and his coauthors have explored the issues fully in Ashish Arora, Andrea Fosfuri, and Alfonso Gambardella, *Markets for Technology: The Economics of Innovation and Corporate Strategy* (Cambridge, Mass.: MIT Press, 2001).

31. Blanchard also manufactured and sold machines. Carolyn C. Cooper, *Shaping Invention: Thomas Blanchard's Machinery and Patent Management in Nineteenth-Century America* (New York: Columbia Univ. Press, 1991), esp. the maps on 194–95.

32. "Patent Assignment Digest," vol. C-1, 51 entries, vol. C-2, 31 entries.

33. The greater number of patents by early patentees is an artifact of the research procedure; I examined patents for post-1835 inventors so that those beginning before 1836 by definition had at least two patents. Civil War disruptions might have reduced assignment among 1856–60 inventors.

34. Territorial assignments were all assigned to others. The movement from one-half to one-tenth was too stark at the extremes, partly because average patents varied from the norm. Categorizing inventors by the year of the first patent understates the decline in territorial patenting because persisting inventors reduced patent assignments over their careers. Isaac Singer, for example, stopped making territorial assignments and bought back earlier assignments.

35. On the postbellum period, see Lamoreaux and Sokoloff, "Inventors, Firms, and the Market for Technology."

36. With only 15 inventors researched, we cannot have much confidence in the strong assignment performance of the South. Part of its success came from border inventors who also resided in Cincinnati and St. Louis.

37. "Rich and Poor Inventors," *Scientific American* 9, May 13, 1854, 277. The journal was not above singling out its own role: the "'Scientific American' has been the greatest agent for rendering patents more valuable, and affording out inventors the means of being better remunerated, than any other influence or agency in our country."

38. "Advertisements," *Scientific American* 9, July 1, 1854, 335.

39. Allen Wilson, for example, assigned his important four-motion sewing machine feed patent to W.P.N. Fitzgerald (who resigned as a patent examiner in 1852), and, according to Wilson's patent file, Fitzgerald contracted to let the Grover and Baker Sewing Machine Co. use it. Fitzgerald was part of a bigger scheme setting up a patent pool in the sewing machine industry.

40. The relation of assignment to continued patenting would have been stronger if I had examined all assignments for each inventor rather than just a few. For inventors with many patents in which later patents followed quickly after the first, the first patent might have been assigned but the assignment not examined.

41. Licensing complicated the picture. George Corliss licensed rights to make his engine but did not assign rights. Yet licensing hardly replaced production; Corliss was an aggressive manufacturer who probably gained most of his returns through sale of his machines. Corliss's licensing is noted in Nathan Rosenberg and Manuel Trajtenberg, "A General-Purpose Technology at Work: The Corliss Steam Engine in the Late-Nineteenth-Century United States," *Journal of Economic History* 64 (March 2004): 61–99.

42. Petra Moser, "How Do Patent Laws Influence Innovation? Evidence from Nineteenth-Century World's Fairs," *American Economic Review* 95 (September, 2005): esp. 1220–21; Petra Moser, "What Do Inventors Patent?" presented at the Von Gremp Seminar for Economic and Entrepreneurial History, UCLA, April 2006.

43. In some ways patent data better reflected actual innovation. Patents had to pass an examination of their novelty, but exhibition entries did not.

44. The share with patents was twice as high as the share of patented American exhibits in surveyed classes two years earlier at the London Crystal Palace Exhibition, where 30 percent of exhibits machinery, agricultural machinery, naval and firearms, civil engineering, and instruments were patented. This difference probably reflected three factors: the higher share of patents for specific groups within the classes surveyed (reapers vs. plows and hoes), the larger share of machinery relative to instruments in 1853 (when the share of instruments patented was lower), and the fact that the 1853 data allowed determination that a tenth of exhibitors were assignees.

45. The overall shares report the ratio of simple averages of innovation and patent shares and as such do not weight for the numbers of innovations or patents. Weighted averages could be used, but the composition of technology types differed greatly between exhibits and patents; textiles and apparel had 4 times as many exhibits as bridges but over 10 times as many patents. Essentially the same conclusions would be reached by either method.

46. An interesting reflection of the bias toward New York City was the continuity of the exhibition with the American Institute's annual fairs. Twenty-nine surveyed exhibits in 1853 received awards in the 1852 American Institute fair. Nineteen came from New York and New Jersey.

47. Indeed, 15 percent of the exhibitors were surveyed in the machinist sample.

48. Calculated from Moser, "What Do Inventors Patent?" table 4.

49. The techniques I studied included only about half of exhibits within their invention classes. See table 4.2 for the distribution by innovation type.

50. *Official Catalogue of the New York Exhibition of the Industry of All Nations, 1853*, 1st rev. ed. (New York: George P. Putnam, 1853), 62, 63, 65, 70. The geographic overlap of patents and inventive usage was less clear in some cases, such as chemicals. It was fractured in others, such as the invention and use of cotton gins, in which gins were mostly patented and made in the North. As harvesting exhibits, the West ascended in usage, invention, patenting, machine manufacturing, and exhibitors.

51. The patent system may have supported a tendency of Americans to concentrate more on mechanization. This may have been one reason why agriculture and other machinery constituted almost 23 percent of U.S. 1853 exhibits, compared to about 6 percent for British exhibitors and 4 percent for all foreign exhibitors.

52. Zorina Khan, *Democratization of Invention,* 28–65; Moser, "How Do Patent Laws Influence Innovation?" The greater propensity to patent in the United States was one reason why U.S. exhibitors in the Crystal Palace Exhibition had higher shares of innovations patented in a wide range of patent types.

53. Evans felt the absence of knowledge was the "greatest difficulty" facing beginning inventors. Ferguson, *Early Engineering Reminiscences,* 38.

54. Learning also occurred from inventions not patented in the United States through publication or observation. I focus on learning related to patenting specifically, though many diffusion mechanisms were the same.

55. Daniel R. Headrick, *When Information Came of Age: Technologies of Knowledge in the Age of Reason and Revolution, 1700–1850* (Oxford: Oxford Univ. Press, 2000).

56. "Important to Inventors," *Scientific American* 12, June 13, 1857, 319.

57. "$37,500 Saved to Inventors in One Year," *Scientific American* 2, February 4, 1860, 101. An 1850 patent examiner's report corroborated that patent agents did not seek patents for half of their inquiries on grounds of lack of novelty. *ARCP,* 1850, 310.

58. Patent File 9092.

59. "A Visit to the Patent Office at Washington," *Scientific American,* n.s. 1, August 6, 1859, 102.

60. Of course, their job was to determine novelty and serve their client, keeping the information secret until the patent application had been acted on, and there is little evidence of unscrupulous agents patenting others' inventions in their own name. Yet the learning served examiners and agents in their jobs and in other engineering activities.

61. *ARCP,* 1843, 3; *ARCP,* 1852, vii; *ARCP,* 1853, 17; *ARCP,* 1859, 1.

62. Reprinted in Walterscheid, *To Promote the Progress of Useful Arts,* 499.

63. "Patent Office," *North American Review,* n.s. 11 (October 1826): 298; *Transactions of the American Institute,* 17–110.

64. *ARCP,* 1852, 377.

65. Patent publication also served other purposes. Manufacturers might learn of solutions to problems they faced and contact the inventor to explore using the patent. A study of patent claims informed manufacturers about the precise novelty in a patent, thus affecting decisions about royalty payments. The 1839 *ARCP* notes that its cumulative index protected manufacturers from the fraudulent claims of owners of spurious patents.

66. *ARCP,* 274. The Patent Office reports did not direct invention to particular targets. Renwick's 1852 report notes one case of targeting; the post office's notice of a new lock contract induced lock invention (377–78). But this was the only such case Renwick discovered that year, suggesting that most invention responded to more diverse stimuli.

67. "Patent Office Report for 1851," *American Polytechnic Journal* 1 (January–June 1853): 178–79.

68. *ARCP,* 1852, 246.

69. Borut, "*Scientific American* in Nineteenth Century America," 100–116.

70. *ARCP,* 1849, 516–17. The 1859 *ARCP* also included an index of patents by keyword but not classified by type.

71. *Scientific American* 12 (1856–57): 251.

72. *ARCP,* 1849, 421.

73. "Patent Office Report for 1851," *American Polytechnic Journal* 1 (January–June 1853): 178.

74. "Scientific Progress," *Scientific American,* n.s. 1, October 1, 1859, 225.

75. *ARCP,* 1865, 8.

76. Ross Thomson, *The Path to Mechanized Shoe Production in the United States* (Chapel Hill: Univ. of North Carolina Press, 1989), 106–7.

77. The fact that there were so few examples of invention directed by learning from patents relative to the large number of examples of other forms of learning itself suggests that patenting may not have played a central role. Data on the of the readership of technical journals, together with readers' locations and occupations, would have come closer to a direct test, but such data are unavailable.

78. Some of these crossover patents involved complementary technologies integral to the same production process, and others were distant complements (such as the steam engines used to power some textile works). But most were not. The furniture, furnaces, lamps, tools, boilers, engines, firearms, saws, and methods to cast, photograph, and navigate for which Dexter Chamberlain received patents were not mere auxiliaries to his printing press. For an industry study of crossover invention, see Ross Thomson, "Crossover Inventors and Technological Linkages: American Shoemaking and the Broader Economy, 1848–1901," *Technology and Culture* 32 (October 1991): 1018–46.

79. Why randomly sampled inventors in each category averaged 3.7 patents while those in the all-inventor sample averaged 1.7 requires explanation. The difference has two sources. First, surveyed sectors had more persisting inventors because established capital goods firms and markets for patents existed and because machinists and scientific occupations were more heavily represented. Second, and more important, surveying all patents of inventors from any one category overcounts inventors with patents in more than one category because they can be sampled more than once. Patents are added from other categories without adding inventors from those categories. This results in some inventors appearing in more than one sector, including Rufus Porter, whose 24 patents included steam engines and clocks, and John Goulding, whose 31 patents combined textiles and firearms. For this reason totals cannot be compared to the all-inventor sample. Like children in the fictional Lake Wobegon, all of whom are above average, randomly sampled patentees in every type of patent could have averaged more patents than randomly sampled patentees in general.

80. We know occupations of about 80 pre-1836 inventors, but directories supplied less information about their network status; case studies reveal that many listed simply as machinists were in fact part of relevant networks.

81. The per capita inventor indices were more disparate than for the all-inventor sample, because the industries concentrated more in the East. Yet even for the all-inventor sample, New England still led with an index of 2.25, and the South trailed, with an index of 0.17.

82. The all-inventor sample suggests that technological occupations were important, if less central, in other industries.

83. John Nader, "The Rise of an Inventive Profession: Learning Effects in the Midwestern Harvester Industry, 1850–1890," *Journal of Economic History* 52 (June 1994): 397–408.

84. Later firms learned from patents. Edison, for example, had his workers search electrical patents in several countries for ideas about light and power inventions.

85. "Reminiscences of Sewing Machine Inventors," *Scientific American* 14, October 30, 1858, 61.

86. It is possible that inventors' later patents were shaped by interactions around earlier patents. Successful inventors often formed long-run ties to agents that involved services to take out and assign patents. Undoubtedly, some discussed inventive possibilities. Samuel Morse, for example, used the services of Charles Page and Leonard Gale when both were patent examiners and at one point assigned Gale a share of his 1840 patent (Post, *Physics, Patents, and Politics;* "Patent Assignment Digest," M-1:40). It thus could have been the case that ongoing relations with patent agents, examiners, and engineers provided useful direction to inventors.

87. At times inventions preceded employment as agents or Patent Office personnel. Here the causality might have been reversed; activity as inventors may have created skills and predispositions for jobs as agents or examiners. In the case of agents and examiners most patents were received after they had begun these professions and thus plausibly resulted from learning within it. In the case of shoe manufacturing, to confine attention to patents after inventors have entered a particular occupation leads to much the same conclusions as looking at all patents. The same probably is true here. Thomson, *Path to Mechanized Shoe Production,* 111–14.

88. "Patent Assignment Digest," vol. B-1, 8 entries; vol. B-2, 27 entries.

89. Lemuel Jenks Records, Baker Library, Harvard Business School; "Patent Assignment Digest," vol. J-1, 15 entries. For a description of postbellum patent agents' activities, see Sokoloff and Lamoreaux, "Inventors, Firms, and the Market for Technology."

90. Post, *Physics, Patents, and Politics,* 160.

91. About three-quarters of patenting occupations were agents, model makers, patternmakers, or draftsmen in the six sectors and the all-inventor sample. The other quarter listed their occupation as inventor, though many changed to other occupations, including patent agents and manufacturers. Several agents were not listed as such in business directories. Moreover, several agents listed in directories show up here as engineers, suggesting the lack of specialization and the mobility between the two groups.

92. "National Convention of Inventors," *Scientific American* 4, March 24, 1849, 210.

93. *Transactions of the American Institute of the City of New York for the Year 1852,* 3–4, 17–18, 473–505.

Chapter 8. The Social Basis of Innovation

1. "Twenty-five Years: A Retrospect," *Scientific American* 15, September 15, 1866, 180.

2. "Twenty-five Years: A Retrospect," 180; "The Scientist, Inventor, and Mechanic," *Scientific American* 20, April 10, 1869, 233.

3. Schumpeter makes the explanatory problem more difficult by interpreting innovation as the act of entrepreneurs driven not by social contexts but by extraordinary personal qualities. This feature derived from his effort to conceive innovation in the confines of a changeless general equilibrium. He recognized that past changes condition present changes, noting that "every process of development creates the prerequisites for the following." *Theory of Economic Development* (New York: Oxford Univ. Press, 1991), 64. Yet he considered it illegitimate to explain change through such historical linkages, insisting that present change be understood without regard to the past or to underutilized resources in the present. His view may have been based on his efforts to interpret innovation consistently with neoclassical equilibrium theory as it existed in his time. He makes similar arguments in *Business Cycles* (New York: McGraw-Hill, 1939), but *Capitalism, Socialism and Democracy* (New York: Harper, 1942) breaks from this interpretation in allowing for permanent innovation by a corporation through organized R&D.

4. On underutilized knowledge and diversification, see Edith Penrose, *The Theory of the Growth of the Firm,* 3rd ed. (White Plains, N.Y.: Oxford Univ. Press, 1959); Ross Thomson, "The Firm and Technological Change: From Managerial Capitalism to Nineteenth-Century Innovation and Back Again," *Business and Economic History* 22 (Winter 1993): 99–134. Joel Mokyr perceptively analyzes knowledge development, access costs, and innovation in *The Gift of Athena: Historical Origins of the Knowledge Economy* (Princeton: Princeton Univ. Press, 2002).

5. Brooke Hindle and Steven Lubar, *Engines of Change: The American Industrial Revolution, 1790–1860* (Washington, D.C.: Smithsonian Institution, 1986), 125–46; L.T.C. Rolt, *George and Robert Stephenson: The Railway Revolution* (New York: St. Martin's, 1962).

6. American firms also benefited from proximity to users. Hindle and Lubar, *Engines of Change,* 133.

7. U.S. Treasury Department, "Steam-Engine" (1839), 25th Cong., 3rd sess. (serial no. 345), H. Doc. 21.

8. This began a long stream of major engineers associated with the B&O, including Benjamin Latrobe, son of the eminent civil engineer, who extended the B&O to Washington and west from Harpers Ferry. On federal involvement, see Forest G. Hill, *Roads, Rails, and Waterways: The Army Engineers and Early Transportation* (Norman: Univ. of Oklahoma Press, 1957); Colleen Dunlavy, *Politics and Industrialization: Early Railroads in the United States and Prussia* (Princeton: Princeton Univ. Press, 1994), 56–59; *A Biographical Dictionary of American Civil Engineers,* 2 vols. (New York: American Society of Civil Engineers, 1972 and 1991); Daniel Hovey Calhoun, *The American Civil Engineer: Origins and Conflict* (Cambridge, Mass.: Technology Press, MIT, 1960).

9. John Stevens, *Documents Tending to Prove the Superior Advantages of Rail-ways and Steam-Carriages over Canal Navigation* (1812; rpt., Boston: Baker Library, 1936). Stevens secured railroad acts from New Jersey and Pennsylvania, built a small-scale train, received two railroad patents, but did not complete a working railroad.

10. The articles began virtually with the inception of the journal with articles taken from British publications. See "Railways," *Journal of the Franklin Institute* 1

(1826): 147–49; "Proposition for a General Iron Rail-way, with Steam-engines, to Supersede the Necessity of Horses in All Public Vehicles," *Journal of the Franklin Institute* 1 (1826): 193–94. Americans also wrote about railroads, including the illustrated article: "Pennsylvania Society for the Promotion of Internal Improvements in the Commonwealth," *Journal of the Franklin Institute* 1 (1826): 10–17.

11. John H. White Jr., *A History of the American Locomotive: Its Development, 1830–1880* (New York: Dover, 1968); Hindle and Lubar, *Engines of Change.*

12. The Steam Engine Report of 1838 lists the firms that made the locomotives operated by each railroad, providing knowledge of the diversity of locomotives used by the same railroad and customers of locomotive firms. English locomotives concentrated in the South, which used under one-quarter of all locomotives but over half of English imports. U.S. Treasury Department, "Steam-Engine." On the centrality of railroads and master mechanics to the communication of techniques, see Steven W. Usselman, *Regulating Railroad Innovation: Business, Technology, and Politics in America, 1840–1920* (Cambridge: Cambridge Univ. Press, 2002), esp. 70–75.

13. Prominent engineers were identified in *A Biographical Dictionary of American Civil Engineers.* On military engineers and shared knowledge, see Robert G. Anglevine, *The Railroad and the State: War, Politics, and Technology in Nineteenth-Century America* (Stanford: Stanford Univ. Press, 2004), 64–99; Dunlavy, *Politics and Industrialization,* 58–64, 154–55. On movement from the Erie Canal, see Elting E. Morison, *From Know-how to Nowhere: The Development of American Technology* (New York: Basic Books, 1974), 40–50.

14. Merritt Roe Smith, "Becoming Engineers in Early Industrial America," Program in Science, Technology, and Society pamphlet no. 13 (Cambridge, Mass.: MIT, 1990). Other examples abound. Early B&O construction trained many prominent engineers, including Wendel Bollman, who became foreman of bridges and master of the road for the B&O; Ellis Chesbrough, who later worked with Long and McNeill and was engineer on New England and Ohio railroads; Henry Ranney, who was chief engineer for the Lexington & Ohio and the New Orleans & Nashville in the mid-1830s; and Squire Whipple, who surveyed other railroads and developed bridge designs. On machinists' networks in railroads, see David R. Meyer, *Networked Machinists: High-Technology Industries in Antebellum America* (Baltimore: Johns Hopkins Univ. Press, 2006), chap. 6.

15. Jervis worked on the railroad from its beginnings. As engineer of the Delaware and Hudson, a Pennsylvania coal canal, he ordered four locomotives from Britain to be run on inclines. Used in 1829, they were the first locomotives in the United States, though they failed and were put in storage. F. Daniel Larkin, *John B. Jervis: An American Engineering Pioneer* (Ames: Iowa State Univ. Press, 1990); Morison, *From Know-how to Nowhere, 49–58;* White, *History of the American Locomotive,* 33–34, 239–41; Hindle and Lubar, *Engines of Change,* 129–43. Early invention was widespread, including Peter Cooper, who, according to his autobiography, built his famous Tom Thumb for the B&O to show that locomotives could run effectively on sharply curving tracks. Peter Cooper, *A Sketch of the Early Days and Business Life of Peter Cooper: An Autobiography* (New York: s.n., 1877).

16. Many of Baldwin's innovations concerned production methods that improved efficiency and durability, a concern he had exhibited in the mid-1820s when he developed one of the first U.S. improvements on the most important industrial machine tool, the engine lathe, just transferred from Britain. M. Baird & Co. Baldwin Locomotive Works, *Illustrated Catalogue of Locomotives* (Philadelphia: J. B. Lippincott, 1871).

17. Sampled from keywords in U.S. Patent Office. *Subject Matter Index of Patents for Inventions Issued by the United States Patent Office from 1790 to 1873, Inclusive* (Washington, D.C.: Government Printing Office, 1874).

18. U.S. Department of Commerce, *Historical Statistics of the United States, Colonial Times to 1970* (Washington, D.C.: Government Printing Office, 1975), Q 321; Albert Fishlow, *American Railroads and the Transformation of the Ante-bellum Economy* (Cambridge.: Harvard Univ. Press, 1965), 315–40.

19. U.S. Census Office, Manufacturing Manuscripts from the Eighth Census, 1860 (available in national archives and in state archives in Conn., Del., Md., N.H., N.J., and N.Y.).

20. U.S. Census Office, Manufacturing Manuscripts from the Eighth Census, 1860. Many specialized in locomotives, but others continued to produce textile machinery, steam engines, and other equipment. In 1860 Mason produced locomotives valued at $80,000 and textile machinery valued at $250,000. Thomas Rogers made 90 locomotives valued at $765,000, in addition to textile machinery. The Danforth Locomotive Company made 36 locomotives and added textile machinery valued at $268,000. Amoskeag was yet more diversified, making 12 locomotives valued at $100,000, 75 steam engines, and $320,000 worth of other machinery and castings. Firms were somewhat larger than locomotive firms listed in table 5.2 because some large firms classified as textile machinery firms made locomotives. White, *History of the American Locomotive,* 19–21. The published census states that Baldwin and Norris made 168 locomotives in 1860, which exceeds other estimates.

21. John K. Brown, *The Baldwin Locomotive Works, 1831–1915* (Baltimore: Johns Hopkins Univ. Press, 1995), 165–83.

22. Baldwin's experience suggests how financing needed to innovate rested on networks, not the universal capital markets of economic theory. His and many other early locomotive firms were partnerships of those with technical knowledge and capital. Credit often came from suppliers and local banks knowing Baldwin's partnerships well. Railroads were typically corporations, but they too relied on networks through insider lending or state and local financing. On insider lending, see Naomi Lamoreaux, *Insider Lending: Banks, Personal Connections, and Economic Development in Industrial New England* (Cambridge: Cambridge Univ. Press, 1994). On public financing of railroads, see Carter Goodrich, *Government Promotion of American Canals and Railroads, 1800–90* (New York: Columbia Univ. Press, 1960). On Baldwin and railroad networks, see Brown, *Baldwin Locomotive Works,* 36, 92–106; Baird, *Illustrated Catalogue;* White, *History of the American Locomotive,* 449–50; Meyer, *Networked Machinists,* chap. 6.

23. Campbell described the advantage of his locomotive in an *American Railway Journal* article: "Where increased power is required, the weight and size of the boiler

and machine can be increased in a ratio of 8 to 6 over ordinary engines, and the adhesion is increased upon the rails by having two pairs of driving or propelling wheels under the *hindmost end*, instead of one pair as in the usual way." He secured a civil engineer, whose equations showed the superiority of his locomotive over Baldwin's. Quoted in U.S. Treasury Department, "Steam-Engine," 170.

24. For example, Campbell assigned to Eastwick, "full license to make, construct and vend to be used in any part of the US or elsewhere." Likewise, Harrison assigned Baldwin the "right to use and vend; only at their manufactory" and—removing an earlier threat—absolved Baldwin and his purchasers "from any liabilities by reason of prior use of said Patent Right." In such assignments the inventors retained the right to license to other firms. Quote for Campbell from U.S. Patent Office, "Patent Assignment Digests" (National Archives, College Park, Md.), C-1:7; see also 32, 41, and 51. Quote for Harrison from "Patents Assignment Digests," H-1:82; see also 58, 72, and 73.

25. White, *History of the American Locomotive,* 47–50, 151–57, 167–69, 452–53.

26. Ibid. Some of these changes were patented, but many were not. They were widely shared, spread by knowledge sharing, worker mobility, and publication. They resembled the process Robert C. Allen called "collective invention." "Collective Invention," *Journal of Economic Behavior and Organization* 4 (March 1983): 1–24. Railroad firms had good reason to cooperate because, operating in largely separate territories, they complemented each other in shipping goods across railroad lines. Baldwin exemplified the incremental path of locomotive change. He was a conservative designer who favored using fewer, simpler parts, and as such opposed the 4-4-0. Recognizing the need for more traction and power, he developed new forms of six-wheeled engines that had four or even six driving wheels. By 1845 he licensed the Campbell and Harrison patents and adopted the more powerful 4-4-0, which weighed 20 tons. From the early 1840s Baldwin and other manufacturers increased fuel efficiency by using more complicated engine cutoffs. Baldwin only reluctantly adopted simpler link-motion cutoffs in the 1850s. Altogether, Baldwin took out ten patents for locomotives through 1865, four related steam engine patents, and one patent for railroad wheels. Most failed, and none were revolutionary. But several improved engine durability and performance. His workers also invented. Matthew Baird, a foreman, copatented a spark arrestor in 1842. In the mid-1850s Baird, now a partner of Baldwin, developed a fire arch to improve combustion in coal-burning furnaces. Baird, *Illustrated Catalogue;* Baldwin patents.

27. Patents were selected from a listing of all patents through 1873 based on the key words *locomotives, car brakes, railway car couplings, railway cars, railway switches,* and *railways.* Other categories, including spark arrestors and car couplings without reference to railways, were not included, though many pertained to railroads. The sample has the merit of consistency before and after 1836, when modern patent numbering and classification began.

28. Location provides another link of invention with usage. If knowledge communication was linked to the railroad network, then patenting would have spread geographically with the spread of the railroad. Railroads were largely located along the Atlantic seaboard until the late 1840s, and 96 percent of railroad patents were located in that area through 1845, led by 83 percent in the Mid-Atlantic States. When railroad investment

grew in the West and Southwest after 1848, patenting did as well, so that these regions received 22 percent of patents from 1846 through 1865. Yet patenting disproportionately concentrated in the Mid-Atlantic and New England states; the ratio of railroad patents to railroad receipts was twice as high in these regions as in the rest of the country. Patenting concentrated particularly in urban centers of locomotive production and machinists.

29. Usselman, *Regulating Railroad Innovation,* 61–96. As Usselman documents, licensing was common, extending the range of patent usage (67–68, 104–7).

30. Others followed similar paths into railroad invention. Henry Waterman invented brick and cotton presses and nail-cutting machines before turning to locomotives, cutoff valves, boilers, and car springs, interspersed with ships, saws, reaping machines, gas regulators, and steelmaking techniques. For him invention had become a way of life.

31. William Sellers & Co., "Order Book" (Hagley Library and Museum, Wilmington, Del.). Railroads were even less important in precision and mass production machine tools. A leading firm, Brown & Sharpe, sold universal milling machines to four locomotive firms and screw machines to seven, only 6 and 9 percent, respectively, of the sales of these machines. Brown & Sharpe, *A Brown and Sharpe Catalogue Collection* (Mendham, N.J.: Astragal, 1997). Machine tool inventions were sampled from U.S. Patent Office, *Subject Matter Index of Patents.*

32. One author, upon publishing detailed drawings of locomotives and analysis of steam locomotion immediately after the Civil War, put such knowledge in perspective: "The construction and working of a locomotive can only be learned in a machine shop and on the road. It is vain to suppose that mere skill in drawing . . . or ever so wide a knowledge of tables of steam generation, expansion and pressure, will make a practical engineer." G. Weissenborn, *American Locomotive Engineering and Railway Mechanism* (Felton, Calif.: Glenwood, 1969).

33. Patenting was important, but unpatented inventions were common in railroad networks. Railroads benefited from the availability of British inventions and of American inventions such as the Jervis truck without U.S. patent protection. Here the absence of patents supported diffusion but only because other institutions communicated knowledge. Many patented inventions were licensed widely, including Campbell's 4-4-0 and Harrison's equalizing bar. Patents did not create entry-preventing advantages. As invention accelerated, the prospect of licensing and litigation costs increased, and railroads became reluctant to purchase patents. Already in 1865, the *Scientific American* wrote that railroad companies have "never manifested a willingness to pay patentees," and this policy would be institutionalized in railroad trade associations. "Our Patent System," *Scientific American* 13, July 1, 1865, 7; White, *History of the American Locomotive,* 48; Brown, *Baldwin Locomotive Works.* On the monopsonistic organization of the market for inventions, see Usselman, *Regulating Railroad Innovation,* 97–139.

34. The nearly simultaneous but unconnected inventions of Walter Hunt, John Greenough, and George Corliss in the United States attest to the recognition that mechanized sewing was possible and advantageous. Each succeeded as an inventor but not of sewing machines. Thomson, *Path to Mechanized Shoe Production,* 78; William T. Hutchinson, *Cyrus Hall McCormick: Seed-Time, 1809–56* (New York: Century Co., 1930).

35. Mokyr called the telegraph a macroinvention because it commercialized wholly different technologies and relied on kinds of knowledge just originating. It was a far more radical change than the locomotive, which built on well-established technologies. Experimental electric telegraphs followed scientific advances quickly, beginning with impractical electrostatic telegraphs. Using early-nineteenth-century advances, techniques emerged quickly and widely in Britain, Germany, and, in Joseph Henry's 1831 experiment, the United States. Joel Mokyr, *The Lever of Riches: Technological Creativity and Economic Progress* (New York: Oxford Univ. Press, 1990), 13, 122–24; Joel Mokyr, *Gift of Athena.* For an overview of telegraph development, see Alexander J. Field, "Telegraph," in *The Oxford Encyclopedia of Economic History,* ed. Joel Mokyr (Oxford: Oxford Univ. Press, 2003), 5:90–92.

36. In these linkages Morse resembled another artist, Robert Fulton. Fulton had worked as a civil engineer and naval innovator and knew virtually all the major steamboat inventors. On the birth of the Morse system, see Thompson, *Wiring a Continent;* James D. Reid, *The Telegraph in America and Morse Memorial* (New York: Derby Bros., 1879); and Paul Israel, *From Machine Shop to Industrial Laboratory: Telegraphy and the Changing Context of American Invention, 1830–1920* (Baltimore: Johns Hopkins Univ. Press, 1992), 24–56. On Morse's life, see Carleton Mabee, *The American Leonardo: A Life of Samuel F. B. Morse* (New York: Octagon Books, 1969).

37. Hutchinson, *Cyrus Hall McCormick,* 28–98.

38. Thomson, *Path to Mechanized Shoe Production,* 73–79.

39. Thompson, *Wiring a Continent;* Reid, *Telegraph in America;* Mabee, *American Leonardo.* On the role of networks, see Israel, *From Machine Shop to Industrial Laboratory,* 57–86. On Page's contribution, see Robert C. Post, *Physics, Patents, and Politics* (New York: Science History Publications, 1976). For a contemporary examination of the Morse system, see "Electro-Magnetic Telegraph," *Journal of the Franklin Institute* 20 (November 1837): 323–25. Alfred Vail wrote one of its first histories, *The American Electro-Magnetic Telegraph* (Philadelphia: Lea & Blanchard, 1845), which angered Joseph Henry for ignoring his contribution. Soon after, world histories were published, including Tal P. Shaffner, *The Telegraph Manual* (New York: Pudney & Russell, 1859).

40. In one key change Morse dropped his earlier coding system—which translated words into numbers and numbers into dots and dashes—with the direct depiction of letters as sequences of dots and dashes. Codes were chosen by examining the frequency of letters in writing. The first Morse code was adopted in 1838, refined in 1844, and later modified in International Morse code, when the familiar three dots, three dashes, and three dots came to represent s-o-s.

41. Hutchinson, *Cyrus Hall McCormick,* 174–249.

42. Thomson, *Path to Mechanized Shoe Production,* 73–92; Cooper, *Invention of the Sewing Machine,* 19–38.

43. Personal relations also helped provide financing, including friends and family (Howe and McCormick) and the network associates who subscribed to the Magnetic Telegraph Co. Reid, *Telegraph in America,* 115.

44. Competition extended outside the economy. Morse argued for his system against optical telegraphs when the federal government considered financing a system and was

well represented in courtrooms. When trying to patent his telegraph in England, he met Charles Wheatstone and learned of other telegraphs; he refused to become Wheatstone's U.S. agent and no doubt worried when Wheatstone received a U.S. patent just before he did.

45. On Morse's patent assignments, see "Patent Assignment Digest," M-1:50, 67. The dozens of Morse assignments provide good evidence on the expansion of the telegraph. Later telegraph companies widened the range of shareholders, though many shareholders in early companies also invested in later ones.

46. Thompson, *Wiring a Continent*; Reid, *Telegraph in America*. On the relation to state government policies, see Tomas Nonnenmacher, "State Promotion and Regulation of the Telegraph Industry, 1845–1860," *Journal of Economic History* 6 (March 2001): 19–36.

47. Kendall tried to set standards, but national coordination only came through competition, bankruptcies, and consolidation that led to the domination of Western Union in 1866.

48. Hounshell, *From the American System to Mass Production,* 153–64; Thomson, *Path to Mechanized Shoe Production,* 93–105. On technological change in agriculture, see Leo Rogin, *The Introduction of Farm Machinery in Its Relation to the Productivity of Labor in the Agriculture of the United States during the Nineteenth Century,* Univ. of California Publications in Economics, vol. 9 (Berkeley: Univ. of California Press, 1931); John Nader, "Learning Effects and the Pace of Technological Change: The Case of the Midwestern Farm Implement Industry, 1850–1890" (Ph.D. diss., New School for Social Research, 1991); John Nader, "The Rise of an Inventive Profession: Learning Effects in the Midwestern Harvester Industry, 1850–1890," *Journal of Economic History* 52 (June 1994): 397–408. Surging sales of reapers in the early 1850s rested on its cost, the size of the farm, the price of labor and grain, the extent of cooperative usage, and improvements in reapers. The strong literature on reaper diffusion began by pointing to the importance of a threshold farm size large enough to spread the cost of the reaper over the farm's output. Subsequent debate concerned whether reapers were shared and whether reaper improvements increased productivity. See Paul A. David, "The Mechanization of Reaping in the Ante-Bellum Midwest," *Industrialization in Two Systems: Essays in Honor of Alexander Gerschenkron,* ed. in Henry Rosovsky (New York: Wiley, 1966), 3–39; Alan L. Olmstead, "The Mechanization of Reaping and Mowing in American Agriculture, 1833–1870," *Journal of Economic History* 35 (June 1975): 327–52; Alan L. Olmstead and Paul W. Rhode, "Beyond the Threshold: An Analysis of the Characteristics and Behavior of Early Reaper Adopters," *Journal of Economic History* 55 (March 1995): 27–57.

49. Table 8.5 differs from table 5.2 because it includes firms for which locomotives were secondary products and excludes agricultural machinery firms that did not make reapers.

50. The centrality of owner-inventors in reaper firms in the 1850s gave way to invention by employees and independent inventors in later decades. See Nader, "Learning Effects" and "Rise of an Inventive Profession."

51. Assignment records indicate, for example, that three sewing machine inventors and two harvester inventors categorized as patent agents or inventors assigned pat-

ents to their own companies making these innovations. They were not recategorized to avoid biasing the study of assignments in favor of network inventors.

52. The fire alarm telegraph was another example. Trained at Dartmouth, Moses Farmer superintended repairs of a Massachusetts telegraph from 1847. An active experimenter, he invented an automatic circuit closer, which became the basis for his fire alarm telegraph. He and a partner got an appropriation from the city of Boston to develop and introduce the telegraph, which spread to other cities through assignments. He later developed batteries, duplex telegraphs, rubber insulation, and a host of other electrical improvements. James D. Reid, *Telegraph in America,* 370–76; Thomson, *Path to Mechanized Shoe Production,* 118–32; Moses G. Farmer, Moses G. Farmer Papers, 1830–93 (Los Angeles: UCLA Young Research Library).

53. Brown & Sharpe, *Brown and Sharpe Catalogue Collection,* 20–21; Joseph W. Roe, *English and American Tool Builders* (New Haven, Conn.: Yale Univ. Press, 1916); Nathan Rosenberg, "Technological Change in the Machine Tool Industry, 1840–1910," *Perspectives on Technology* (Cambridge: Cambridge Univ. Press, 1976); Hounshell, *From the American System to Mass Production,* 67–83, 159–70.

54. Of course, other factors supported widespread innovation. Demand was conducive, though it also was supportive in countries that imported U.S. innovations or invented on their own. Demand was not enough; many countries imported techniques but did not develop them. The United States had little of the opposition to innovation that had destroyed the sewing machines invented by the French tailor Barthelemey Thimonnier. Yet openness to innovation would have meant little if the United States had not had the capability to develop and produce innovations.

Chapter 9. Technological Leadership

1. Jean Baptiste Marestier, *Memoirs on Steamboats of the United States of America,* trans. Sidney Withington (Mystic, Conn.: Marine Historical Association, 1957), 62–63.

2. This makes the task more manageable, though it underestimates the role of technological change because developments in some sectors supported innovation elsewhere by increasing demand, profitability, or investment.

3. One could argue that eighteenth-century craft woodworking and metalworking led industrialization. Certainly, they constituted a platform without which mechanization would have been much slower. But while they supplied conditions, they were largely static, with few innovations that could lead other industries.

4. Joseph W. Roe, *English and American Tool Builders* (New Haven, Conn.: Yale Univ. Press, 1916), 225; George S. Gibb, *The Saco-Lowell Shops: Textile Machinery Building in New England, 1813–1949* (Cambridge: Harvard Univ. Press, 1950); John W. Lozier, *Taunton and Mason: Cotton Machinery and Locomotive Manufacture in Taunton, Mass., 1811–1861* (New York: Garland, 1986).

5. Roe, *English and American Tool Builders,* 125.

6. Roe, *English and American Tool Builders,* 125; Gibb, *Saco-Lowell Shops; Dictionary of American Biography.*

7. Kilburn, Lincoln Machine Co., Business Records, 1835–1929 (Baker Library, Harvard Business School, Boston).

8. [Louis McLane], *Documents Relative to the Manufactures in the United States* (1833; rpt., New York: Augustus M. Kelley, 1969); Roe, *English and American Tool Builders,* 225; J. Leander Bishop, *A History of American Manufactures from 1608 to 1860* (Philadelphia: E. Young, 1868), 3:344–47; Victor S. Clark, *History of Manufactures in the United States, 1607–1860* (Washington, D.C.: Carnegie Institution, 1916), 517–19.

9. Gibb, *Saco-Lowell Shops,* 90, 198; Lozier, *Taunton and Mason,* 426.

10. Locks and Canals. "Letter Books." DA1-6 (Baker Library, Harvard Business School. Boston); David R. Meyer, *Networked Machinists: High-Technology Industries in Antebellum America* (Baltimore: Johns Hopkins Univ. Press, 2006).

11. *The Manchester Directory, and a Business Directory, for 1860* (Boston: Adams, Sampson & Co., 1860), 58, advertising department; Roe, *English and American Tool Builders*; Bishop, *A History of American Manufactures,* vol. 3; Lozier, *Taunton and Mason,* 246; Meyer, *Networked Machinists.*

12. David Wilkinson, "Reminiscences," in *The New England Mill Village, 1790–1860*, ed. Gary Kulik, Roger Parks, and Theodore Z. Penn (Cambridge, Mass.: MIT Press, 1982), 90.

13. U.S. Senate, "Petition of David Wilkinson," *Reports of Committees,* serial set vol. 512, no. 103 (Washington, D.C.: Wendell & Van Benthuysen, 1847).

14. Zachariah Allen, "History of Cotton Manufacture in America," in *The New England Mill Village, 1790–1860,* ed. Gary Kulik, Gary, Roger Parks, and Theodore Z. Penn (Cambridge, Mass.: MIT Press, 1982), 149.

15. Merritt Roe Smith, *Harpers Ferry Armory and the New Technology* (Ithaca, N.Y.: Cornell Univ. Press, 1977), 104, 122–24; Roe, *English and American Tool Builders.*

16. Bishop, *History of American Manufactures,* 3:361.

17. Quoted in Carroll Pursell, *The Machine in America* (Baltimore: Johns Hopkins Univ. Press, 1995), 49.

18. Andrew Ure, *The Cotton Manufacture of Great Britain* (London: Charles Knight, 1836), 2:62–82; David J. Jeremy, *Transatlantic Industrial Revolution: The Diffusion of Textile Technologies between Britain and America, 1790–1830s* (Cambridge, Mass.: MIT Press, 1981), 206–8; David J. Jeremy, "Technological Diffusion: The Case of the Differential Gear," in *Artisans, Entrepreneurs and Machines: Essays on the Early Anglo-American Textile Industries, 1770–1840s* (Aldershot, Hampshire: Ashgate Publishing, 1998).

19. Gibb, *Saco-Lowell Shops,* 179.

20. Guy Hubbard, "Development of Machine Tools in New England," *American Machinist* 60 (1924): 255–58, 271–74; Roe, *English and American Tool Builders,* 195–97.

21. Louis C. Hunter, *A History of Industrial Power in the United States, 1780–1930,* vol. 1: *Waterpower in the Century of the Steam Engine* (Charlottesville: Univ. Press of Virginia, 1979), 462–71.

22. George H. Corliss Papers (John Hay Library, Brown University, Providence, R.I.); Nathan Rosenberg and Manuel Trajtenberg, "A General-Purpose Technology at Work: The Corliss Steam Engine in the Late-Nineteenth-Century United States," *Journal of Economic History* (March 2004): 61–99.

23. To these effects on mechanization must be added its role in developing factory management, corporate organization, and capital markets.

24. Roe, *English and American Tool Builders,* 120.

25. Nathan Rosenberg, "Technological Change in the Machine Tool Industry, 1840–1910," in *Perspectives on Technology* (Cambridge: Cambridge Univ. Press, 1976); David A. Hounshell, *From the American System to Mass Production, 1800–1932* (Baltimore: Johns Hopkins Univ. Press, 1984).

26. Rosenberg, "Technological Change"; Hounshell, *From the American System;* Roe, *English and American Tool Builders,* 207–11; Brown & Sharpe Manufacturing Co., Records, 1833–1994 (Providence: Rhode Island Historical Society).

27. "Wheeler and Wilson's Sewing Machine Manufactory," *Scientific American* 8, January 3, 1863, 1–3, quote on 3; Hounshell, *From the American System to Mass Production*, 68–75; Ross Thomson, *The Path to Mechanized Shoe Production in the United States* (Chapel Hill: Univ. of North Carolina Press, 1989), 141. The *Scientific American* recognized that interchangeability was incomplete when it wrote, "It is remarkable also, to see a machine shop where no files are used; we mean by this, none in comparison to what are generally consumed" (3).

28. Karl Marx, *Capital: A Critique of Political Economy* (London: Vintage, 1976), 1:499.

29. Elhanan Helpman, ed., *General Purpose Technologies and Economic Growth* (Cambridge, Mass.: MIT Press, 1996), 4, 32–43; T. Bresnahan and M. Trajtenberg, "General Purpose Technologies: 'Engines of Growth,'" *Journal of Econometrics* 65 (1995): 83–108; Nathan Rosenberg, "Uncertainty and Technological Change," in *The Mosaic of Economic Growth,* ed. Ralph Landau, Timothy Taylor, and Gavin Wright (Stanford: Stanford Univ. Press, 1996), 334–53; Rosenberg and Trajtenberg, "General-Purpose Technology at Work."

30. Richard G. Lipsey, Cliff Bekar, and Kenneth Carlaw, "What Required Explanation?" *General Purpose Technologies and Economic Growth,* ed. Elhanan Helpman (Cambridge, Mass: MIT Press, 1998), 15–54. They also listed printing presses, organizational GPTs, such as the factory system and mass production, and "near GPTs," including machine tools. These GPTs strongly overlapped with the industry dynamics considered earlier. GPTs are detailed in Richard G. Lipsey, Kenneth I. Carlaw, and Clifford T. Bekar, *Economic Transformations: General Purpose Technologies and Long Term Economic Growth* (Oxford: Oxford Univ. Press, 2005), 169–218.

31. Another 28 percent of engines made other manufactures, pumped water and salt wells, and mined coal. Author's calculations, U.S. Treasury Department, "Steam-Engine," 25th Cong., 3rd sess. (serial no. 345), H. Doc. 21, 1839.

32. Rosenberg and Trajtenberg offer a caution about the role of innovational complementarities. After careful searching, they found no clear-cut cases in which the Corliss engine propelled complementary innovation. "General-Purpose Technology at Work," 67n.

33. *Harris' General Business Directory of the Cities of Pittsburgh and Allegheny* (Pittsburgh: Isaac Harris, 1841), n.p.; *The Directory of the City of Boston* (Boston: George Adams, 1850), 31. See chap. 5 on the share of firms making engines.

34. Among major innovators without patents, those trained in steam engineering and railroads also concentrated in construction, transportation, and power inventions.

35. Louis C. Hunter, *A History of Industrial Power in the United States, 1780–1930*, vol. 2: *Steam Power* (Charlottesville: Univ. Press of Virginia, 1985), 551; Henry R. Worthington, *The Worthington Steam Pumping Engine: History of Its Invention and Development* (N.p.p., 1876); Henry Rossiter Worthington," *Dictionary of American Biography; Eighty Years' Progress of the United States* (Hartford, Conn.: L. Stebbins, 1867), 259–65.

36. The engine's effects on ongoing technological change extended outside the economy. Governmental involvement in river clearance, partly using steam-powered snag boats, improved steamboat productivity and proved a model for later infrastructural interventions. The problem of steam boiler explosions involved the government and engineering associations in organized research; both this research and the solution to the problem—the regulation of the generation and use of industrial products—affected later technological change. Problems of engine efficiency and design provided a powerful incentive for the development of the science of thermodynamics, in which the government played an interesting role. The navy commissioned a series of experiments by Benjamin Isherwood to determine the role of the expansive use of steam in engine efficiency. In the context of his controversial experiments, he noted that heat was lost when steam condensed into water in the engine cylinder. This became an important problem in the postwar development of thermodynamics (Hunter, *Steam Power,* 439–45). The internal dynamics of technology within any industry would remain shaped by, and would affect, governmental policies and scientific development.

37. Moreover, innovators trained outside early industrializers who invented in these sectors concentrated in instruments other than clocks and in new kinds of armaments, including the Gatling gun, revolting turrets, and torpedoes, often late in the period.

38. Machinists, applied scientists, and inventive occupations made up a higher share in these industries than they did overall. Among randomly sampled patentees they constituted 30 percent of inventors with known occupations, holding 40 percent of patents. The typically higher inventor and patent shares in table 9.5 had two sources. First, these 12 technology types were often leading centers of mechanization, in which higher shares of technically trained would be expected. Second, by including not just the patents originally sampled but all other patents by each inventor, inventors in these sectors had more than one chance to be selected.

39. The distinction of internal and crossover patents is arbitrary in the sense that it depends on the choice of which patent types to sample; a textile patent is "internal" to the textile sample but a crossover in other samples. This affected patent shares relative to inventor shares. Several prominent firearms manufacturers, for example, had many firearms patents and one or two machine tool patents. This was reflected in technological occupations having a share of internal firearms patents under their inventor share and a share of crossover patents under their inventor share in machine tools. Technological occupations typically had higher inventive breadth.

40. Early industrializers were, however, particularly underrepresented in some sectors; they received less than half the share of agricultural and science-based innovations, as did innovators in general.

41. Joseph Schumpeter, *The Theory of Economic Development* (Cambridge: Harvard Univ. Press, 1961), 64.

42. L.T.C. Rolt, *The Railway Revolution* (New York: St. Martin's, 1960).

43. Lipsey, Bekar, and Carlaw call machine tools "near-GPTs" because they applied only to manufacturing, but in fact they were used in transportation, mining, and every sector having to maintain machinery and build tools ("What Required Explanation?" 47). In the antebellum period general-purpose machine tools such as the engine lathe and planer were better examples of GPTs than mass production machine tools such as the turret lathe.

44. Iron-making techniques were also important. Adequate supplies of pig and malleable iron were needed to make machinery; U.S. deficiencies in this area would have been more constraining if imports had not been available.

45. Engineers often moved among activities. Horatio Allen, for example, was trained in mathematics at Columbia and worked on canals before designing railroads. He helped design the Croton Aquaduct and roads and, developing his mechanical side, made marine engines.

46. Moses G. Farmer, Moses G. Farmer Papers, 1830–1893 (Los Angeles: UCLA Young Research Library), box 3, folder 6.

47. "A. Davis' Compound Magneto Electric Machines," Lowell City Directory (Lowell, Mass., 1859), 230. Other electrical machines claimed to treat tuberculosis and other maladies.

48. Because only 56 inventors had known occupations before 1835, I studied all inventors. Average patenting was higher for those with occupations, but the pattern of increasing crossover patenting after 1835 was the same; crossover patents for early inventors in all early-industrializing sectors increased from 1.8 before 1835 to 2.9 after that year.

49. Engineers and applied scientists not trained in such early sectors did not conform to the pattern; their crossover share fell from two-thirds to three-tenths. Early crossover innovators were all mechanicians innovating in new lines. The high share of internal innovators after 1835 is deceptive. Many had been trained as engineers before the railroad, gained employment on railroad construction, then innovated in the field. Similarly, chemists often applied techniques to different chemicals, and those innovating in telegraphs had first learned elsewhere.

50. Eugene S. Ferguson, "Metallurgical and Machine-Tool Developments," in *Technology and Western Civilization,* ed. Melvin Kranzberg and Carroll W. Pursell Jr. (New York: Oxford Univ. Press, 1967), 1:266.

51. That breadth and complementarity of innovation has bearing on the issue of whether any technique was indispensable. Much has been written about whether the railroad, considered in isolation, accelerated U.S. growth. The best analysis suggests that the railroad modestly increased antebellum growth, with particularly strong effects in promoting agricultural expansion in the West. Backward linkages to machin-

ery and iron were important, but the railroad was not decisive for either one. Yet asking what the U.S. economy would have looked like had the railroad not existed is a dubious question because the prior development of technology made it highly unlikely that the railroad would not have been introduced or that locomotives would not have been produced domestically. If we then ask what would have happened had the conditions leading to the rapid introduction of the railroad been absent—had engine producers, textile machinists, and civil engineers not existed—it becomes clear that much of the development of capitalism would have been affected. Albert Fishlow, *American Railroads and the Transformation of the Ante-bellum Economy* (Cambridge: Harvard Univ. Press, 1965). Even more widely recognized than Fishlow is Robert Fogel, whose analysis focuses primarily on the postbellum period. Robert W. Fogel, *Railroads and American Economic Growth* (Baltimore: Johns Hopkins Univ. Press, 1964).

Chapter 10. Fruition

1. Joseph H. Davis, "An Annual Index of U.S. Industrial Production, 1790–1915," *Quarterly Journal of Economics* 119 (November 2004): 1189.

2. The account of the high-speed engine is based primarily on Porter's autobiography, *Engineering Reminiscences Contributed to "Power" and "American Machinist"* (New York: John Wiley & Sons, 1908); as supplemented by Otto Mayr, "Yankee Practice and Engineering Theory: Charles T. Porter and the Dynamics of the High-Speed Engine," *Technology and Culture* 16 (1975): 570–602; and Louis C. Hunter, *A History of Industrial Power in the United States, 1780–1930,* vol. 2: *Steam Power* (Charlottesville: Univ. Press of Virginia, 1985), 450–66.

3. Quote from "The Way to Manage an Invention," *Scientific American* 2, May 5, 1860, 297; see also "Machinery Department of the Late Fair of the American Institute," *Scientific American* 2, January 2, 1860, 9; Porter, *Engineering Reminiscences,* 17–33.

4. Porter, *Engineering Reminiscences.* Mayr identifies the uniqueness of the high-speed principle, which the Watt or the Corliss engine could not embody, the means Porter used to incorporate it in his engine, and the path leading him to engineering insights about his engine's success. "Yankee Practice and Engineering Theory," 572–99.

5. Porter's governor was commercially successful, but his engine failed to achieve Corliss's success. His extended stay in England, where Joseph Whitworth made his engine, and his modest skills in running firms limited the engine's diffusion. But the engine had wide effects on the design of high-speed engines over the rest of the century.

6. *The Lowell Directory* (Lowell, Mass., George Adams, 1851), advertisements, 10.

7. Ross Thomson, *The Path to Mechanized Shoe Production in the United States* (Chapel Hill: Univ. of North Carolina Press, 1989), 119–22. For Wickersham's assignments, see U.S. Patent Office, "Patent Assignment Digests" (National Archives, College Park, Md.), esp. W-1:258, 285, 287, and W-2.

8. Thomson, *Path to Mechanized Shoe Production.* For Townsend's assignments, see "Patent Assignment Digests," B-1:220, 233, 242; G-1:233, 279; R-1:216; S-1:308, 311, 313;

S-2:3, 12, 29, 90, 122, 139, 149, 165, 183; W-1:259, 259. On litigation, see Charles H. McDermott, *A History of the Shoe and Leather Industries of the United States* (Boston: J. W. Denehy, 1918), 64–68. On contexts for mechanization, see Blanche Hazard, *The Organization of the Boot and Shoe Industry in Massachusetts before 1875* (Cambridge: Harvard Univ. Press, 1921).

9. Thomson, *Path to Mechanized Shoe Production*, 156–65; for assignments, see "Patent Assignment Digests," B-2:105, 106, 168, 171, 173, 212, 214.

10. Thomson, *Path to Mechanized Shoe Production*, 156–65; *Official Catalogue of the New York Exhibition of the Industry of All Nations, 1853,* 1st rev. ed. (New York: George P. Putnam, 1853), 37.

11. Quoted from Lyman Blake, *Application of Lyman Blake for Extension of Letters Patent* (Boston, 1874), 7, 9, 25; Thomson, *Path to Mechanized Shoe Production,* 161, 163. Royalties from machine usage increased from $38,800 in 1863 to $99,200 in 1864 and $150,800 in 1865, some with army contracts and others with civilian markets. *Shoe and Leather Reporter* 17, July 30, 1874, 1.

12. Grace Rogers Cooper, *The Invention of the Sewing Machine* (Washington, D.C.: Smithsonian Institution, 1968), 60. McKay army sales might have been greater. The army purchased on the order of 8 million pairs of shoes from 1861 through 1864, and the 470,000 pairs constituted about 6 percent of the total. One McKay user, Seth Bryant, claimed to have made 200,000 to 300,000 pairs, and his recorded contracts, amounting to $364,000, suggest that he approached the lower estimate. Many others also made machine-sewed shoes. See Seth Bryant, *Shoe and Leather Trade of the Last Hundred Years* (Boston, 1891), 37, 77,112; Mark R. Wilson, *The Business of War: Military Mobilization and the State, 1861–65* (Baltimore: Johns Hopkins Univ. Press, 2006), 233.

13. One reason why machinists made up so small a proportion is that a wider range of city directories, including many small Massachusetts shoe towns, was consulted than for other technologies. On crossover invention in the industry, see Ross Thomson, "Crossover Inventors and Technological Linkages: American Shoemaking and the Broader Economy, 1848–1901," *Technology and Culture* 32 (October 1991): 1018–46.

14. The seven pegging and sewing machine inventors from other manufacturing occupations were even more prolific largely because two inventors, including Blake, became shoe machinists, and one photographer became a chemist with 18 crossover patents.

15. Thomson, *Path to Mechanized Shoe Production,* 42–44.

16. Harold F. Williamson and Arnold R. Daum, *The American Petroleum Industry: The Age of Illumination, 1859–99* (Evanston, Ill.: Northwestern Univ. Press, 1959), 12–42.

17. Paul H. Giddens, *The Early Petroleum Industry* (Philadelphia: Porcupine Press, 1974), 1–6; Williamson and Daum, *American Petroleum Industry,* 12–24; U.S. Treasury Department, "Steam-Engine" 25th Cong., 3rd sess. (serial no. 345), H. Doc. 21 (1839), 226–29. The drilling of salt wells provides another example of the independent origins of early inventions. It was largely the product of a wood-based society utilizing

craft techniques. Yet its further development relied on the steam engine and metal piping and drilling equipment.

18. Williamson and Daum, *American Petroleum Industry,* 27–60; Christopher J. Castaneda, *Invisible Fuel: Manufactured and Natural Gas in America, 1800–2000* (New York: Twayne, 1999), 13–44. Jennings's patents were surveyed in the study of crossover steam engine inventors; a study of petroleum patents included those of Atwood and Merrill. Philadelphia gaslight investment data are from the 1850 census manuscripts.

19. Williamson and Daum, *American Petroleum Industry,* 63–112, 118; quote on 69. Interestingly, Silliman's father, Benjamin Sr., had published one of the first reports on American petroleum in 1833. Both were heavily involved in geology, as were many chemists who worked in geological surveys and in firms assessing the quality of minerals.

20. Williamson and Daum, *American Petroleum Industry,* 136–89.

21. Williamson and Daum, *American Petroleum Industry,* 206–27.

22. Pittsburgh city directories, 1861–62, 354 and 33, advertisements; 1863–64, 383 and 48–57, advertisements; 1864–65, 366 and 57–77, advertisements.

23. *The Wood and Mann Steam Engine Company, Builders of their Celebrated Patent Portable Steam Engines* (Utica, N.Y.: Curtis & White, 1866), quote on 5.

24. William Haynes, *American Chemical Industry: Background and Beginnings* (New York: D. Van Nostrand, 1954), 1:249.

25. Paul David and Gavin Wright, "Increasing Returns and the Genesis of American Resource Abundance," *Industrial and Corporate Change* 6 (1997): 203–45.

26. Wilson, *Business of War,* 38.

27. Imported firearms often were of lower quality and posed the problem of repairing distinct models. Such repair problems fell on the Springfield Armory, already charged with increasing its output and ensuring the quality of private contractors. Wilson, *Business of War,* 75, 231–32; Felicia Johnson Deyrup, *Arms Makers of the Connecticut Valley, Smith College Studies in History* (Northampton, Mass.) 33 (1948): 177–84; Carl L. Davis, *Arming the Union: Small Arms in the Civil War* (Port Washington, N.Y.: Kennikat, 1973), 105.

28. Wilson, *Business of War,* 231.

29. Quoted from Merritt Roe Smith, "Eli Whitney and the American System of Manufacturing," in *Technology in America,* ed. Carroll W. Pursell (Cambridge, Mass.: MIT Press, 1990), 58; William Sellers & Co., "Visitors Register," 1861–1947, asc. no. 1466 (Hagley Museum and Library, Wilmington, Del.); Deyrup, *Arms Makers of the Connecticut Valley,* 177–204. On the difficulties of the Ordnance Department in purchasing, inspecting, and servicing arms, see Davis, *Arming the Union.*

30. Wilson, *Business of War,* 231; Joseph W. Roe, *English and American Tool Builders* (New Haven, Conn.: Yale University Press, 1916), 175–77, 192–93. Firearms contractors with the federal government are listed in U.S. House of Representatives, "Ordnance Department," *House Executive Documents* 99, 40th Cong., 2nd sess., serial set 1338.

31. Deyrup, *Arms Makers of the Connecticut Valley,* 194.

32. "Machinery for Gun-Making," *Scientific American* 5, August 24, 1861, 113.

33. Richard M. Hoe and Company, Records, 1824–1953 (New York: Columbia University), box 24, Letterbooks, February 3–July 9 1862, esp. 201. Along with 60 rifling

machines for the Springfield Armory, Hoe made rifling machines for a private armory, power-compressing machines for DuPont and Hazard powder companies, and hydraulic presses to compress dry meat and vegetables and shaped shells for Parrott guns and sheet metal for Monitor hulls and turrets. Frank E. Comparato, *Chronicles of Genius and Folly: R. Hoe & Company and the Printing Press as a Service to Democracy* (Culver City, Calif.: Labyrinthos, 1979), 140–45.

34. "Advertisements," *Scientific American* 7, November 15, 1862, 319.

35. Barton H. Jenks, Papers (Hagley Museum and Library, Wilmington, Del.); Deyrup, *Arms Makers of the Connecticut Valley,* 180. On earlier production by contractors, see 1860 manufacturing census manuscripts and J. Leander Bishop, *A History of American Manufactures from 1608 to 1860,* vol. 3 (Philadelphia: E. Young, 1868).

36. "How a Rifled Musket Is Made at the Providence Tool Company's Armory," *Scientific American* 9, November 7 and 14, 1863, 293–94, 308–10, quote on 293. The articles present a detailed description of the armory's techniques.

37. Brown & Sharpe, *A Brown and Sharpe Catalogue Collection* (Mendham, N.J.: Astragal, 1997), 22, 29, quote on 22.

38. Wilson, *Business of War,* 76, 232; Bishop, *History of American Manufactures;* William H. Roberts, *Civil War Ironclads: The U.S. Navy and Industrial Mobilization* (Baltimore: Johns Hopkins Univ. Press, 2002).

39. Porter, *Engineering Reminiscences,* 28.

40. B. Zorina Khan, "Creative Destruction: Technological Change and Resource Reallocation during the American Civil War" (paper presented at the Economic History Association meetings, Toronto, September 2005).

41. That the 28 persisting inventors had nearly as many Civil War inventions as the 68 beginning after 1860 points to the importance of continuity. Data on inventors with occupations probably exaggerates the importance of network inventors a bit because those with no recorded occupation probably had lower network shares. On the other hand, some listed as nonnetwork inventors actually had network links. Christopher Spencer, for example, had worked for Colt but was listed simply as a machinist in city directories.

42. Assignments for new inventors were limited to those issued at the time of the patent because patent assignment records were only consulted for inventors who began by 1860. Others were no doubt assigned during the war.

43. On the development of military arms, see Davis, *Arming the Union.* Heavy ordnance also developed through established private firms, though the Ordnance Department played a more innovative role. Naval armaments advanced through a complex interaction of private innovators, the navy and its shipyards, and established private firms, as the ascendance of Monitor-type ironclads illustrates. Roberts, *Civil War Ironclads.*

44. Brown & Sharpe, *Brown and Sharpe Catalogue Collection.* Production improvements affected heavier machinery as well, notably rolling improvements used on ironclads.

45. Patent data from the technology samples developed in chaps. 3, 5, 6, and 8. For total Civil War shoe output, see Thomson, *Path to Mechanized Shoe Production,* 181.

Chapter 11. The First Innovation System

1. Adam Smith, *The Wealth of Nations* (New York: Modern Library, 1937), 259–60.

2. Bruce Sinclair, "At the Turn of a Screw: William Sellers, the Franklin Institute, and a Standard American Thread," *Technology and Culture* 10 (January 1969): 20–34; Bruce Sinclair, *Philadelphia's Philosopher Mechanics: A History of the Franklin Institute, 1824–1865* (Baltimore: Johns Hopkins Univ. Press, 1974), esp. 308–25.

3. Joseph Whitworth, "Special Report," in *The American System of Manufactures,* ed. Nathan Rosenberg (Edinburgh: Edinburgh Univ. Press, 1969), 389.

4. Joseph P. Ferrie, "The End of American Exceptionalism? Mobility in the United States since 1850," *Journal of Economic Perspectives* 19 (Summer 2005): 199–215.

5. See, for example, the essays in Richard R. Nelson, ed., *National Innovation Systems: A Comparative Analysis* (New York: Oxford Univ. Press, 1993).

6. The conclusions would differ somewhat if all patents were examined, not just those of surveyed inventors. For all U.S. patents from 1836 through 1865, patent per capita indexes were 2.56 for New England, 1.86 for Mid-Atlantic States, 0.16 for the South, and 0.68 for the West. The difference from the ratios for surveyed sectors reflects the choice of technologies developed more in the East and the greater share of eastern inventors with known occupations. Moreover, if patents were examined through 1860 to avoid Civil War dislocations, the South's index rose to 23 percent of the nation's total, and the West's fell to 56 percent. Yet clearly, southern patenting lagged greatly behind the East's by any measure. Interestingly, the South's share of patents grew in the national patent upsurge of the late 1850s; its share increased from 6.0 percent in 1851–55 to 8.3 percent in 1856–60, with the fastest growth occurring in the cotton belt from Georgia through Texas. For aggregate patent data, see U.S. Patent Office, *Annual Report of the Commissioner of Patents* (Washington, D.C.: Government Printing Office, 1892), xii–xiii.

7. Ross Thomson, "Networks, Communal Knowledge, and the Location of Invention in Antebellum America" (presented in the Economic History Association meetings, Austin, Tex., 2007).

8. The urban concentration of invention and manufacturing persisted throughout the century. See Allan R. Pred, *The Spatial Dynamics of U.S. Urban-Industrial Growth, 1800–1914: Interpretive and Theoretical Essays* (Cambridge, Mass.: MIT Press, 1966).

9. On the centrality of the East, see David R. Meyer, *The Roots of American Industrialization* (Baltimore: Johns Hopkins Univ. Press, 2003). Regional specialization of all manufacturing, of particular industries, and of invention persisted after the war and may even have grown. For a survey, see Sukkoo Kim and Robert Margo, "Historical Perspectives on U.S. Economic Geography," in *Handbook of Regional and Urban Economics,* ed. Vernon Henderson and Jacques-François Thisse, vol. 4 (Amsterdam: North-Holland, 2004).

10. William Parker noted the greater prevalence of manufacturing firms in the West than in the South, especially those employing 3 to 10 workers, and attributed the difference to free versus slave labor systems. If, as he felt, greater learning occurs

where manufacturing and towns are more common, then differences of labor systems underpinned the technological divergence of the West and South. See Parker, "Slavery and Southern Economic Development: An Hypothesis and Some Evidence," *Europe, America, and the Wider World: Essays on the Economic History of Western Capitalism* (Cambridge: Cambridge Univ. Press), 1:41–50.

11. Immigrating inventors came from many countries, and the diversity of their technological backgrounds may have brought a wider range of knowledge and capabilities to the United States, providing another advantage of the melting pot.

12. Nathan Rosenberg, *Technology and American Economic Growth* (New York: Harper & Row, 1972); Gavin Wright, "Can a Nation Learn? American Technology as a Network Phenomenon," in *Learning by Doing in Markets, Firms, and Countries,* ed. Naomi Lamoreaux, Daniel M. G. Raff, and Peter Temin (Chicago: Univ. of Chicago Press, 1999), 295–326. Both Hobbs and Colt formed well-known British factories, but neither succeeded and diffusion from them was modest. Rosenberg, *American System of Manufactures,* 10–18.

13. B. Zorina Khan, *The Democratization of Invention: Patents and Copyrights in American Economic Development, 1790–1920* (Cambridge: Cambridge Univ. Press, 2005), 38–65.

14. Paul A. David, "Computer and Dynamo: The Modern Productivity Paradox in a Not-Too-Distant Mirror," *Technology and Productivity: The Challenge for Economic Policy* (Paris: OECD, 1991).

15. A rough measure of assignments is the number of pages in Patent Assignment Digests devoted to assignments from different years. Pages listing annual assignments grew from about 0.7 percent of the entire 1836–63 period in the late 1830s to 7 percent in the late 1850s. Because many early assignments were much longer than later ones, the number of assignments probably rose even more rapidly.

16. We have emphasized factors sustaining the development of technological knowledge, which included feedbacks between science and technology and between invention and diffusion. Such factors were not self-contained. A broader account would consider market growth, investment behavior, organizational innovations, government policy, and resistance to innovation. Technological change in turn integrated markets, reduced prices and costs, affected profitability and competitiveness, supported nontechnological innovations, and shaped public policy.

17. England and the Continent also innovated in ways that the United States did not fully emulate, including iron making, inorganic and organic chemicals, pottery, and the luxury trades. Wide innovation was associated with widespread productivity growth in manufacturing from 1820 to 1860, both in mechanized industries and others. See Kenneth L. Sokoloff, "Productivity Growth in Manufacturing during Early Industrialization: Evidence from the American Northeast, 1820–60," in *Long-Term Factors in American Economic Growth,* ed. Stanley L. Engerman and Robert E. Gallman, NBER Studies in Income and Wealth no. 51 (Chicago: University of Chicago Press, 1986). Sokoloff cautions that technological change was one source of productivity growth, but especially before 1850 organizational innovations, such as those involving specialization, putting-out systems, and factories, were widely important.

18. Max Weber, *General Economic History* (New York: Collier, 1961), 230; Kenneth L. Sokoloff and B. Zorina Khan "The Democratization of Invention during Early Industrialization: Evidence for the United States, 1790–1846," *Journal of Economic History* 50 (June 1990): 363–78.

19. George S. Gibb, *The Saco-Lowell Shops: Textile Machinery Building in New England, 1813–1949* (Cambridge: Harvard Univ. Press, 1950), 80.

20. Rosenberg, *American System of Manufactures,* 331.

21. Zachariah Allen, *The Science of Mechanics* (Providence, R.I.: Hutchins & Cory, 1829), 111.

22. Rosenberg, *American System of Manufactures,* 331–89, quote on 331.

23. Rosenberg, *American System of Manufactures,* 336; Charles T. Porter, *Engineering Reminiscences Contributed to "Power" and "American Machinist"* (New York: John Wiley & Sons, 1908), 58.

24. James M. Usher, *Paris Universal Exposition; 1867* (Boston: Nation Office, 1868).

25. Providence's Hope Iron Works, for example, developed a successful drop press to forge firearm parts, which was used by many armories. It then spread widely and quickly in mass production metalworking. As Bishop wrote in 1868, "Having been thoroughly tested in gun work, and proved it excellence, it has since been adopted in the various shops, where work is struck up in duplicate, such as parts of Sewing Machines, Ploughs, Shovels, Cutlery, Axes, Pickaxes, Kettles, Tools, Harness and Sailmakers' Trimmings, etc." J. Leander Bishop, *A History of American Manufactures from 1608 to 1860* (Philadelphia: E. Young, 1868), 3:389–90.

26. Gloria May Stoddard, *Henry Leland: The Story of the Vermonter Who Created Cadillac and Lincoln* (Shelburne, Vt.: New England Press, 1986), 12–62; David A. Hounshell, *From the American System to Mass Production, 1800–1932* (Baltimore: Johns Hopkins Univ. Press, 1984).

27. Bishop, *History of American Manufactures,* 3:377–401.

28. Paul Israel, *Edison: A Life of Invention* (New York: John Wiley & Sons, 1998), 23–34.

29. B. Zorina Khan and Kenneth L. Sokoloff, "Institutions and Democratic Invention in 19th-Century America: Evidence from 'Great Inventors,' 1790–1930," *American Economic Review* 94 (May 2004): 395–401.

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